

Rethinking biogeoclimatic ecosystem classification for a changing world

Sybille Haeussler

Abstract: Biogeoclimatic ecosystem classification (BEC) has underpinned terrestrial ecosystem management and conservation planning in British Columbia, Canada since the early 1970s, serving the province well for over 40 years as expectations for the use and management of the public land base have evolved. The system is now critically challenged because (1) BEC champions in government, academia, and the private sector are disappearing through retirement and layoffs; (2) BEC is based on outdated notions of climax ecosystems in equilibrium with climate; and (3) the contemporary relevance and intellectual richness of this approach to ecosystem science is not comprehended by a generation of scientists and resource managers grappling with accelerating rates of change in climate and other environmental drivers. This review addresses ways to ensure that BEC remains robust and useful in an uncertain future. The Author proposes that BEC embrace complex systems science. Through a dialectical analysis of alternative paradigms in ecology, it is argued that BEC's holistic, developmental view of terrestrial ecosystems is fundamentally compatible with complexity theory and provides the information content missing from contemporary ecosystem ecology. Two examples of nonlinear modelling (adaptive landscapes and agent-based) to illustrate how the classification system can adapt from a largely linear and equilibrium, to a nonlinear, nonequilibrium perspective of ecosystem dynamics. The BEC program itself must function as a complex adaptive system to survive government downsizing and guide ecosystem management during difficult times, and to challenge and enlighten a new generation of scientists and citizens.

Key words: British Columbia, climate change, complex systems, ecological land classification, history of ecology, nonequilibrium dynamics.

Résumé : La Classification Biogéoclimatique des Écosystèmes (CBE) a supporté l'aménagement des écosystèmes terrestres et la planification de la conservation en Colombie Britannique, au Canada, depuis le début des années 1970, en servant bien la Colombie Britannique pendant plus de 40 ans, alors que les attentes pour les utilisations et l'aménagement des terres publiques, ont évolué. On remet présentement en question ce système, parce que : (1) les champions de la CBE au gouvernement, dans les universités et dans le secteur privé disparaissent suite aux retraites et aux mises à pied; (2) la CBE est basée sur des notions dépassées concernant les écosystèmes climatiques en équilibre avec le climat; et (3) la pertinence contemporaine et la richesse intellectuelle de cette approche aux écosystèmes sont incomprises par une génération de scientifiques et d'aménagistes des ressources, aux prises avec des taux accélérés de changements climatiques et autres forces environnementales. On suggère ici des moyens pour assurer que la CBE demeure robuste et utile dans un futur incertain. L'auteur propose que la CBE embrasse une science complexe des systèmes. En conduisant une analyse dialectique de paradigmes alternatifs en écologie, il soumet que la vue holistique et développementale des écosystèmes terrestres demeure fondamentalement compatible avec la théorie de complexité et fournit le contenu informatif absent de l'écologie des écosystèmes contemporaine. Il utilise deux exemples de modélisation non linéaire (paysages adaptatifs, multiagents) pour illustrer comment le système de classification peut s'adapter d'un équilibre surtout linéaire et équilibré, à une perspective non linéaire, non équilibrée de la dynamique des écosystèmes. Le programme CBE lui-même doit fonctionner comme un système adaptatif complexe pour survivre à la réduction des effectifs gouvernementaux et guider les aménagistes des écosystèmes pendant des temps difficiles, et mettre au défi et éclairer une nouvelle génération de scientifiques et de citoyens.

Mots-clés : Colombie Britannique, changement climatique, système complexe, classification écologique des terres, histoire de l'écologie, dynamique non équilibrée.

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Introduction

In his powerful radio essay series *The Wayfinders: Why ancient wisdom matters in the modern world*, Wade Davis (2009) describes how the master Tahitian mariners skillfully navigated

the vast waters of the Pacific Ocean without a compass or GPS. Their intergenerational learning process involved, among other lessons, having apprentice navigators lash their genitals to the hull of the boat to detect subtle shifts in the frequency, amplitude, and direction of the waves. This is traditional knowledge

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at its most sublimely holistic — the human body as a sensory organ so finely tuned to its environment that it becomes impossible to be lost in the wide open sea.

Science, by contrast, has spent the better part of the past 500 years in pursuit of a more perfect reductionism, building ever more powerful microscopes, telescopes, computers, and particle accelerators that shift the burden of sensory perception and signal processing from human to machine. And yet it is increasingly evident that technological wizardry does not provide solutions to the complex, multidimensional problems that plague humanity and our relationship with the Earth (Ravetz 2004; Chapin et al. 2009). In the 21st century, science has reached a remarkable turning point. It has acquired the theoretical and technological capacity to transcend reductionism, to break down disciplinary boundaries, and to re-embrace holism in the search for solutions to complex problems (Morin 2001; Nicolescu 2002; Wolfram 2002; Kauffman 2008; Gunderson et al. 2010). In many fields of inquiry (McBreen 2002; Moodley and West 2005; Berkes 2008), science is taking a second look at traditional forms of learning to find better ways to blend the incisive power of the scientific method with the wisdom of more integrated perspectives or worldviews. More often than not, that integration takes place within the framework of complex systems science (Holland 1992; Manson 2001; Bar-Yam 2003).

Complex systems (complexity) science is a rational, evidence-based approach to understanding the behaviour of whole systems that provides a common language and suite of analytical tools to improve communication and integration across disciplines (Haeussler and Thorpe 2010). Because it addresses whole-system behaviours beyond the scope of reductionist science, it can help to reconcile the culture clash between scientific and traditional approaches to understanding our world.

This review is not about ancient wisdom or sea-faring Tahitians. It examines a more recent form of traditional ecological knowledge that originated in central and eastern Europe, then made its way to British Columbia (BC), Canada in the aftermath of World War II. Biogeoclimatic ecosystem classification (BEC) is a comprehensive hierarchical system of knowledge about terrestrial ecosystems used throughout BC to describe and interpret ecological conditions and to develop plans for land and resource management at local to provincial scales (Figs. 1 and 2; Pojar et al. 1987; Meidinger and Pojar 1991; BECWeb 2011). This ecological land classification system has been fully integrated into the land use decision-making framework of BC since the 1970s (MacKinnon et al. 1992; Mah et al. 1996), and yet its pre-eminent role is now under threat for scientific, economic, and cultural reasons.

While listening to Davis tell his stories about the Polynesian wayfinders on my car radio, an image came to mind from my own apprenticeship as a young forest ecologist in the 1970s. In the depths of a soil pit, Professor Karel Klinka is texturing a small sample of dirt between the fingertips of one hand and gesturing with a cigarette towards the treetops with the other hand, all the while explaining in rich Czech-accented English how tree, soil, and site are intimately linked.

Klinka, now retired from the Faculty of Forestry at the University of British Columbia (UBC) and previously with the BC Forest Service, was a master practitioner of the art

and science of BEC, a holistic approach to understanding, describing, and communicating about terrestrial ecosystems that embodies some of the best Old World and New World traditions in natural history, ecology, and earth sciences. As he walked through the forest or climbed into a soil pit, like those Tahitian seafarers, Klinka was able to filter the sensory input from the forest (the acrid smell of humus, the wind in the leaves, the spring of the moss under his feet, the angle of the sun against his body, the subtle shades of the top horizons of soil, the intricate branching pattern of a fern, and the tug of gravity on his thighs), through neural networks structured by a long tradition of scholarship and honed through decades of field experience, into an integrated picture of an ecosystem and how it could be managed.

My aims in this essay are twofold. Firstly, I will use BEC as a case study to illustrate that older, holistic traditions of thought, practice, and craftsmanship should be brought back into the scientific mainstream to advance our ability to understand, predict, and respond sensibly to the behaviour of our rapidly changing world. Secondly, I will argue that BEC's integrated approach to ecosystem classification is fundamentally compatible with contemporary theory of complex systems. I will outline how new analytical tools used in complex systems science can strengthen the theoretical foundations of BEC, improve its utility as a decision-aid and inspire and enlighten a younger generation of earth and environmental scientists and ecosystem managers.

Biogeoclimatic ecosystem classification (BEC)

A brief history

The BEC system was initially developed by Vladimir J. Krajina at UBC from 1949 to the 1970s, and further systematized after 1975 through the Ecology Program of the British Columbia Forest Service. Krajina (1905–1993) was a remarkable ecologist, a hero of the Czech resistance, and Member of the Order of Canada and Czechoslovak Order of the Lion. After completing a Ph.D. in botany, he worked in Hawaii, Japan, and Europe before being appointed Associate Professor of geobotany and plant systematics at Charles University, Prague in 1934. War broke out in 1939, and Krajina became a leader of the Czech underground, fighting the Nazi invasion, supplying intelligence to Allied forces and barely escaping execution in a Nazi concentration camp. After the war, he was elected to the Czechoslovakian Parliament and became Secretary-General of the main opposition party, but had to flee following the Communist takeover in 1948 by skiing over the mountains into Austria. Krajina came to Vancouver as a lecturer, then professor of botany at UBC, where he dedicated himself to ecosystem-based management and conservation of the ecosystems of British Columbia (Ceska 1993; Cermak 2000; Jenik 2002).

Working out of an old army hut at UBC, Krajina and 34 graduate students developed a theoretical and practical framework for classification and mapping of forest, grassland, and alpine ecosystems of British Columbia at the climatic and site levels that adapted eastern and western European traditions of geobotany, phytosociology, autecology, and soil science (Krajina 1955, 1958, 1959a, 1959b, 1966, 1965, 1976; Krajina and Orloci 1961; Krajina and Brooke 1969–1970). Although he worked outside of the North American academic

Fig. 1. Classification hierarchies in biogeoclimatic ecosystem classification (BEC). BEC combines methods from classical phytosociology (Braun-Blanquet 1932) and soil survey (Dokuchaev 1883; Simonson 1952; McKeague and Stobbe 1978) to describe ecosystems according to their climate, parent material, topography, soils, and biota. It is a multi-tiered system that hierarchically classifies vegetation, climate and site units. The foundational units (plant association, the biogeoclimatic subzone, site series) are linked together through the concept of a **zonal** site (mid-slope position, moderate slope, west or east aspect, moderately deep soils) where vegetation and soils are deemed to best reflect the influence of regional climate, unmodified by local topographic, soil or microclimatic features such as a perched water table or frost hollow (adapted from Meidinger and Pojar (1991), with permission).

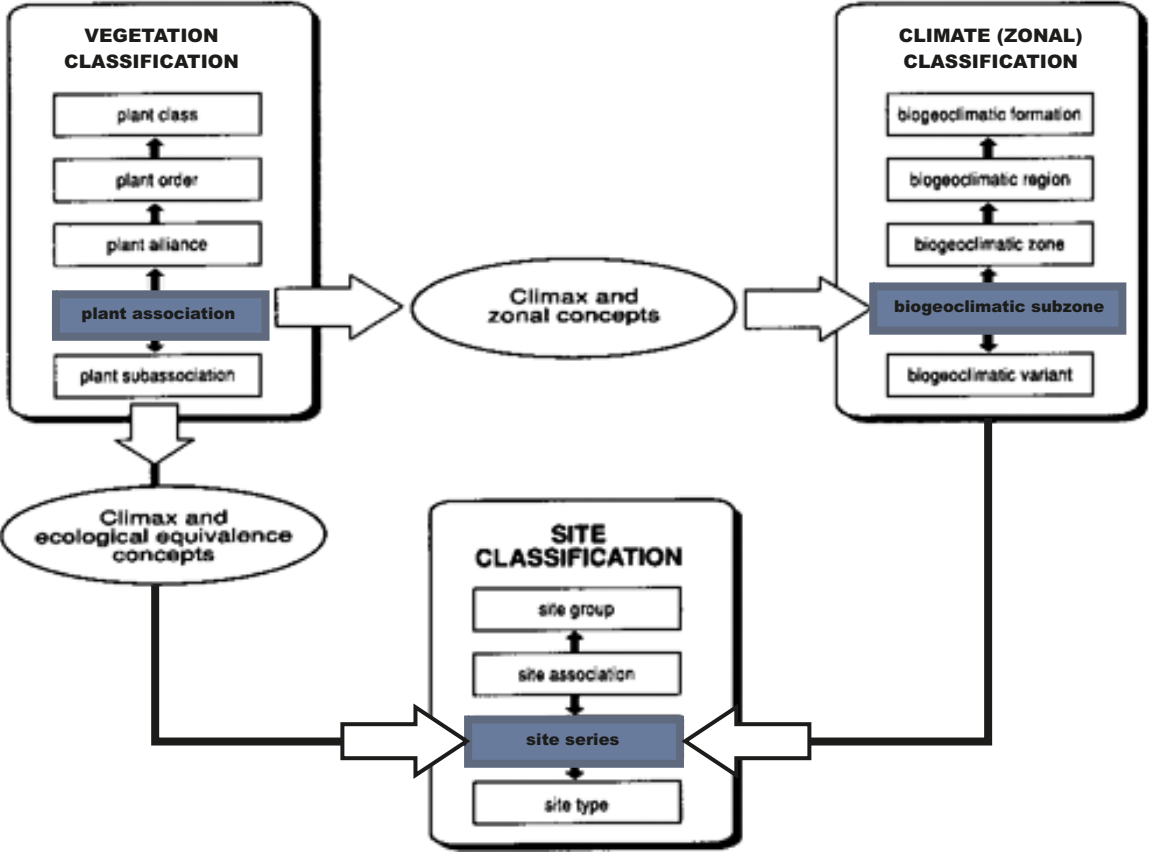
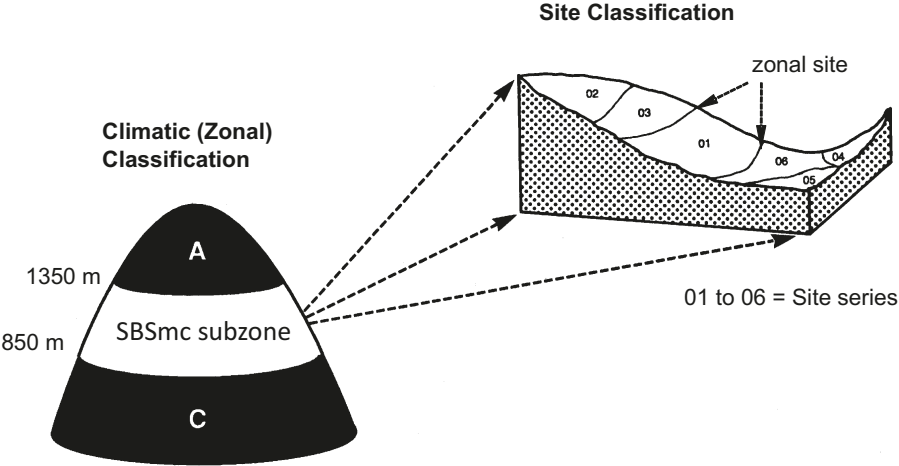


Fig. 2. Relationship between the climate (zonal) and site classifications. A topographic sequence of site series is delineated within each subzone. Each site series is identified by the abbreviated name of a biogeoclimatic zone and subzone, a site series number and the climax plant association. Zonal site series are always numbered 01. Hence, SBSmc/01: Hybrid Spruce – Huckleberry is the name given to the zonal site series for the moist cool subzone of the Sub-Boreal Spruce Zone." (adapted from Meidinger and Pojar (1991), with permission).



mainstream, choosing to self-publish rather than submit to independent peer review, and favoured arcane latinized terminology, Krajina was prescient in anticipating trends in conservation biology and forest management, and used his political skills and force of personality to gain influence with government. He lectured undergraduate forestry students on the importance of understanding whole ecosystems, was a vocal critic of industrial forest practices, and tirelessly lobbied the government of British Columbia to establish a representative system of legally protected ecological reserves (Province of BC 1971; Krajina 1974) and to base forest inventory, growth-and-yield prediction, harvest, and reforestation practices on ecological principles and ecologically defined management units.

Karel Klinka, a Czech immigrant and the last of Krajina's doctoral students, was instrumental in introducing BEC into forestry decision-making when he became a pedologist for the Forest Service in the early 1970s. He and others refined site-scale ecosystem mapping techniques and adapted Krajina's work into field decision-aids for tree species selection and slashburning (Klinka and Pendl 1976; Klinka and Skoda 1977; Klinka et al. 1984). Klinka's success in applying Krajina's ideas to silvicultural challenges of the day convinced the Forest Service to expand the ecological classification program province-wide. Dick Annas, another Krajina student, was hired as the first provincial coordinator of the BEC program in 1976. Annas and his successor, Del Meidinger, both plant ecologists, worked closely with soil and terrain specialists to ensure that the program maintained a strong earth sciences focus rather than devolving into a vegetation classification (Bailey 2009), and to balance the European geobotanical perspective with North American soil and land-capability mapping techniques (Valentine et al. 1978; Mac-Millan et al. 2007).

Issues and applications

Krajina's (1969) intentions were to provide an ecological foundation for forestry and protected areas management in British Columbia, and to a significant extent his vision was realized with the institutionalization of BEC as a descriptive framework at all levels in British Columbia after 1975. When forestry and land management practices in the province faced significant challenges or conflicts because of changes in public expectations or new international conventions and standards, the BEC system has repeatedly provided a rational scientific framework for tackling the problem (Table 1). Most recently, BEC is being used as a platform for environmental monitoring (BC Ministry of Forests, Mines and Lands 2010) and climate change impact projections (Hamann and Wang 2006; DeLong et al. 2010; Coops et al. 2010).

Challenges faced by biogeoclimatic ecosystem classification

Despite serving British Columbia well for roughly 40 years, BEC is now critically challenged for several reasons:

1. The first generation of BEC champions in government, academia, and the private sector have now largely retired or were lost through organizational restructuring. With 60% cuts to research staffing since 2000 (Parfitt 2010), BEC specialists in the BC Forest Service are struggling

to maintain critical mass. Just as once happened to the Tahitian navigators (Davis 2009), there is no replacement generation of ecologists and pedologists receiving the mentoring and field experience required to properly understand, apply and train others in the use of BEC, and to continue to refine and adapt the system for new applications. In BC, as elsewhere (Basher 1997; Ferguson et al. 1997), specialization, contracting out and implementation of results-based management (Vold 2003; Parfitt 2010) have also contributed to a breakdown in the generalist tradition of site diagnosis and prescription development in silviculture and other resource management disciplines.

2. Biogeoclimatic ecosystem classification is based on outdated notions of climax ecosystems in equilibrium with climate and local topographic and edaphic conditions — the “Balance of Nature” paradigm (Botkin 1992; Wu and Loucks 1995; Walker and Pellatt 2008). In addition to being out of step with mainstream thinking in ecology and earth sciences, which have rejected the equilibrium perspective (Johnson et al. 1990; Pickett et al. 1992), these ideas are increasingly at odds with the reality of BC's land base. Discrepancies between the described climatic regimes of mapped ecological units (Meidinger and Pojar 1991) and current data are rapidly widening (Rodenhuis et al. 2007). Moreover, the classification was developed from the 1950s to 1970s, when BC's landscape was dominated by unfragmented and undeveloped tracts of forest, tundra, and wetland (Holland 1976; BC Ministry of Forests, Mines and Lands 2010). Ecologically intact land now covers less than one third of the province, while road networks, disturbance rates, and alien species are increasing (BC Ministry of Environment 2007). With these changes, the notion of site potential — a single, deterministic successional trajectory to a climax — is quickly becoming as abstract in BC as in more densely populated and developed North American landscapes.
3. The dominant scientific community in ecology and environmental sciences is largely indifferent to the demise of BEC. Although academics and educators are making the transition from equilibrium and reductionist scientific perspectives to a nonequilibrium, nonreductionist view, few understand the intellectual richness and contemporary significance of the field ecology tradition that is being lost. Because BEC and its European antecedents are structured knowledge systems (Bui 2004) not easily comprehended by the uninitiated, few contemporary North American ecologists are aware of their potential to advance and enrich the emerging scientific worldview.

A new kind of science

Paradigm shifts, scientific pluralism, and dialectics

Most of us are familiar with the concept of a paradigm shift, where one dominant system of thought or beliefs is displaced by a newer, better, or more fashionable model — not through incremental change, but rather through a revolution of ideas. A tipping point occurs where the majority viewpoint suddenly switches from scepticism or disdain to acceptance and enthusiasm. Al Gore's *An inconvenient truth* (Gore

Table 1. Application of the biogeoclimatic ecosystem classification (BEC) system to resource management and land use challenges in British Columbia.

Land and resources management issue	Example references
BC contribution to the International Biological Programme (IBP) worldwide survey of conservation sites (1964–1974)	Krajina 1974
Ecological reserves selection and establishment	Krajina 1973; Krajina et al. 1978
Tree species selection and stocking standards for reforestation	Klinka et al. 1984; Silviculture Interpretations Working Group 1993
Slashburning guidelines to avoid site degradation	Klinka et al. 1984
Silvicultural techniques for backlog reforestation	Coates et al. 1987
Wildlife habitat mapping and habitat supply modelling	Banner et al. 1985; Wilson et al. 2003
Provincial old growth strategy	Old Growth Strategy Project 1992
Provincial protected areas strategy	Province of BC 1993
Biodiversity management guidelines (Forest Practices Code Guidebook)	Parminter 1995
Biodiversity monitoring (ecological communities at risk)	Conservation Data Centre 2010
Forest productivity and site index assessment (SIBEC)	Mah and Nigh 2003
Sustainable forest management planning criteria and indicators	FSC Canada 2005; Tembec 2005
Forest and rangeland monitoring (Forest and Range Practices Act)	BC Ministry of Forests and Range 2008
Environmental assessment process for major project development	Terrane Metals Corp. 2008
First Nations land claims and reconciling traditional ecological knowledge and use with western science and management	Olive and Carruthers 1998; Daly 2005
Inventory and monitoring of non-timber forest resources	Keefer et al. 2008; Kranabetter et al. 2009.
Climate change impacts assessment and monitoring	Cumming and Burton 1996; Hamann and Wang 2006; Eddington et al. 2009
Climate change adaptation strategy development	Symmetree Consulting Group 2009

2006) comes to mind. The idea of revolutionary progress in science (Kuhn 1962), or society at large, is founded on the notion that scientific models or value systems will keep improving. It often seems instead that there is little forward progress, that we flip-flop back and forth from one unsatisfactory idea or state to another (e.g., more government intervention in the economy, followed by deregulation, followed by more intervention, and so on). Scientific pluralism (Kellert et al. 2006), like pluralism more generally, is the idea that there is no single best scientific model or explanation and that understanding and progress are best achieved by maintaining openness to multiple approaches or modes of thought. Wave-particle duality in the physics of light (Greiner 2001) is an excellent example.

A closely related idea is that of *dialectic* (Levins and Lewontin 1985). In dialectic theory, progress is made through the continual unification of opposites; the newer, better approach or scientific model finds a way to accommodate two opposing concepts that formerly seemed irreconcilable. By focusing on two contradictory ideas at the same time — embracing the paradox, so to speak, the dialectic method achieves a transcendence of opposites that enables the imagination to leap to a higher level.

The history of Lamarckian and Mendelian paradigms in genetics (Fig. 3) serves as a case in point. It exposes the polarizing, political power of a paradigm, and demonstrates the merits of scientific pluralism. Old ideas can become new again. New scientific discoveries and conceptual models make it possible to unify ideas that once appeared diametrically opposed. My purpose here is to show that complex systems theory provides a way to reconcile a dominant schism in ecology, and that BEC, by embracing complex systems science, can make the necessary leap of imagination towards better ecosystem management in British Columbia and elsewhere.

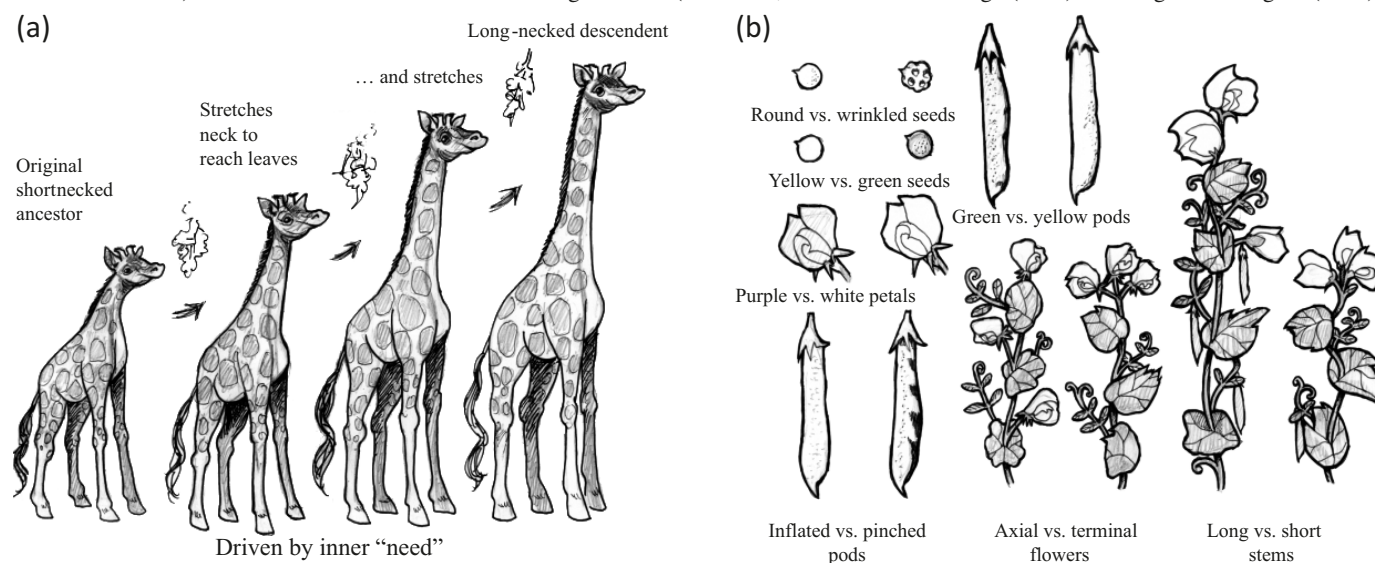
Clementsian and Gleasonian paradigms in ecology

There are strong parallels between the Lamarckian and Mendelian paradigms in genetics and what have come to be known as the Clementsian and Gleasonian paradigms in terrestrial ecology. The American ecologist Frederick Clements (1874–1945) developed a holistic perspective of ecosystems as meta-organisms that progress from a juvenile or pioneering stage to a stable, mature climax community (Clements 1916, 1936). In continental Europe and Russia, a similar organismic and developmental understanding of soil formation (Dokuchaev 1883; Ponomareva 1969), plant community organization (Cajander 1909; Braun-Blanquet 1932; Du Rietz 1936), and ecosystem dynamics (Sukachev 1944) arose over the same period. These ideas continued to flourish in Europe and Russia, through schools of phytosociology and geobotany that established terminology-rich taxonomies or classification systems for soils, plant communities (phytocenoses), and ecosystems (biogeocoenoses) (Becking 1957; Sukachev and Dylis 1968; Cooper 1968).

In English-speaking countries, the individualistic viewpoint exemplified by Henry Gleason (1882–1975) whereby organisms respond individually to gradients in resource availability rather than as discrete integrated communities, was taking hold (Gleason 1926, 1939). Individualistic approaches were bolstered by a new focus on quantitative and predictive methods in ecology (Whittaker 1951, 1953) and earth sciences (Jenny 1941) as a way to duplicate the rapid progress being made in the physical sciences. Early in the 20th century, Ernest Rutherford, a Nobel Prize-winning physicist, had quipped that “all science is either physics or stamp collecting” (Birks 1962), and this dismissive attitude to research that did not involve rigorous testing of theory through experimentation gradually filtered out into the life and applied sciences, and from major research universities into

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Fig. 3. (a) Lamarckian inheritance, named after Jean Baptiste de Lamarck (1744–1829), is the notion that characteristics acquired during an organism's lifetime are passed on to its progeny. (b) Gregor Mendel (1822–1884), the father of genetics, famously showed with garden peas that traits are passed on through the segregation and independent assortment of what later came to be known as genes. By the early 20th century, Mendelian inheritance had thoroughly supplanted Lamarckism as the ruling paradigm. Thereafter, Lamarck and his giraffes came to be widely caricatured, even reviled, in the West after being promoted in the 1940s and 1950s by Trofim Lysenko, the powerful director of Soviet biology under Joseph Stalin. Recent developments in epigenetics show, however, that genes (Mendelian inheritance) can be switched on or off in offspring according to the environmental conditions experienced by their parents (Lamarckian inheritance). In Norway spruce seedlings, for example, the timing of bud-set is influenced by temperatures experienced by the mother tree during seed development (Kvaalen and Johnsen 2008). It seems that Lamarck knew something after all. (A. Coates, modified from Savage (1977) and Singer and Hilgard (1978)).



smaller, regionally focussed institutions. English-speaking scientists with a nonindividualistic perspective of ecosystem dynamics gravitated to the new science of ecosystem ecology (Odum 1953) which reduced ecosystems to flows of energy and nutrients — removing whole organisms and taxonomy (i.e., the *information content* of ecosystems) from the picture — so as to accommodate quantitative and experimental approaches.

Political ideology during the Cold War years also played a key role in the general denigration of the Clementsian paradigm, which came to be associated with socialism and communism (Westman and Peet 1982; Barbour 1996; Pojar 2000). In BC, however, an influx of charismatic Czech and Hungarian botanists and foresters following World War II (Adamovich and Sziklai 1970; Kovar 2002), helped to maintain strong connections to a European intellectual tradition of vegetation and ecosystem science that was effectively marginalized in most of the Anglo-American world.

The difficulty is that once the techniques, tools, and pedagogy of a particular paradigm take hold (e.g., classification versus linear modeling) they acquire a momentum of their own (Levins and Lewontin 1985) that further constrains the ability of those operating within the paradigm to think or communicate outside of their comfort zone. As the physicist Werner Heisenberg (1958) famously noted, the object of study (in this case, the ecosystem) acquires characteristics of those who study it. Despite attempts at reconciliation (Goodall 1963; Whittaker 1972), amplifying feedback mechanisms such as language barriers, development of jargon, competitive political and intellectual cultures, specialized software, scientific journals and meetings, drove the competing approaches further apart. In the English-speaking academic

world, the Gleasonian paradigm in ecology became dominant, driving the Clementsian paradigm out of mainstream scientific journals and university departments.

In North America, the Clementsian paradigm persisted among small pockets of field ecologists such as the BEC program of the BC Forest Service, and the National Forest habitat type classification work groups within the US Forest Service (Daubenmire 1952; Cooper et al. 1991). These groups, working in the mountainous West within government-funded ecological land classification programs, were sufficiently large to maintain a critical mass. Efforts to export classification systems based on climax ecosystem concepts east of the Rocky Mountains (e.g., Sivak 1987) failed to gain traction, for reasons associated with both the sociopolitical climate and the lack of rugged terrain (see adaptive landscape modeling below). In the universities, immigrants from Europe with phytosociological and geobotanical training either fell into step with the prevailing US-dominated culture in ecology, or became academically marginalized.

The irony of these historical developments is that the Clementsian foundations of the BEC program are very well suited for adapting to the new scientific concepts of nonlinear and nonequilibrium dynamics, just as the program is disintegrating from the combined pressure of reductionist science and market-driven government policies. The concept of an ecosystem as fundamentally developmental, with physical and biological interactions constraining its trajectory through time — not unlike an embryo developing into a full-grown organism — is particularly important. In order for the new nonequilibrium mathematical tools to be applied for practical use, a scientist or practitioner must be able to conceive of an ecosystem as a self-organized, adaptive system with emergent

properties that are more than the sum of the behaviour of individual components (Levin 1998; Gunderson and Holling 2002). More importantly, a framework like the BEC system is needed to translate that abstraction into on-the-ground reality, for example, in modelling how terrestrial ecosystems will respond to a warming climate in concert with rapid shifts in land use and influxes of invasive species.

The recent surge of interest in modelling how forest and rangeland ecosystems will respond to climate change can serve as a catalyst for updating and revitalizing BEC and investing in synthetic approaches for modelling ecosystems as simultaneously holistic and individualistic. In the following, I will illustrate how this process can take place from both a theoretical and an applied perspective.

The state factor model: Applying linear thinking to complex ecosystems

The state factor equation of ecosystems is attributed to Hans Jenny (1941; Amundson and Jenny 1997). Jenny was trained in classical soil science, a discipline deeply influenced by the Russian soil science master Victor Dokuchaev (1883), who held a profoundly integrative and developmental view of soil formation. Jenny was keen to apply the new quantitative and reductionist methods to creating a modern, more predictive soil science. He proposed that soils (S), and later ecosystems (E), be expressed in an equation as a function of climate (C), organisms (O), topography (G), parent materials (P), and time (T):

$$[1] \quad S \text{ or } E = f(C, O, G, P, T)$$

The holistic view that prevailed at that time, and that still underlies BEC, was that all of these factors are interconnected and simultaneously interact with one another (Fig. 4). When Karel Klinka stood in a soil pit, this was his mental model. An equation that expresses these interrelationships mathematically

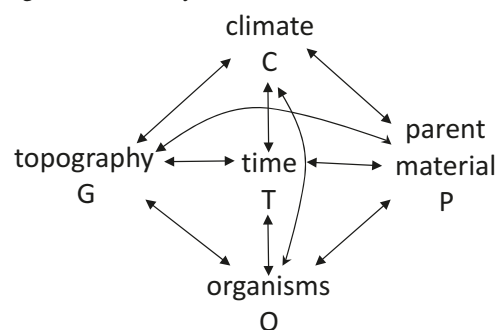
$$[2] \quad E = \alpha C^a \beta O^b \gamma G^c \delta P^d \varepsilon T^e$$

could not be solved with the analytical and computational tools available at the time, and remains intractable to the present day. The solution is to linearize eq. [2] by adding each factor as an independent effect together with all possible interactions among two to five factors:

$$[3] \quad E = a_1 C + a_2 O + a_3 G + a_4 P + a_5 T + b_1 C b_2 O + b_3 C b_4 G + b_5 C b_6 P + b_7 C b_8 T + c_1 O c_2 G + c_3 O c_4 P + c_5 O c_6 T + d_1 G d_2 P + d_3 G d_4 T + e_1 P e_2 T + f_1 C f_2 O f_3 G + f_4 C f_5 O f_6 P + f_7 C f_8 O f_9 T + f_{10} C f_{11} G f_{12} P + f_{13} C f_{14} G f_{15} T + f_{16} C f_{17} P f_{18} T + g_1 O g_2 G g_3 P + g_4 O g_5 G g_6 T + g_7 O g_8 G g_9 T + h_1 G h_2 P h_3 T + i_1 C i_2 O i_3 G i_4 P + i_5 C i_6 O i_7 G i_8 T + i_9 C i_{10} O i_{11} P i_{12} T + i_{13} C i_{14} G i_{15} P i_{16} T + j_1 O j_2 G j_3 P j_4 T + k_1 C k_2 O k_3 G k_4 P k_5 T$$

Because eq. [3] is unreasonably cumbersome, the reductionist

Fig. 4. A nonlinear state factor model of soils and ecosystems underlies biogeoclimatic ecosystem classification.



and parsimonious solution is to assume that factor interactions are unimportant and can be dropped from the equation unless demonstrated to be statistically significant:

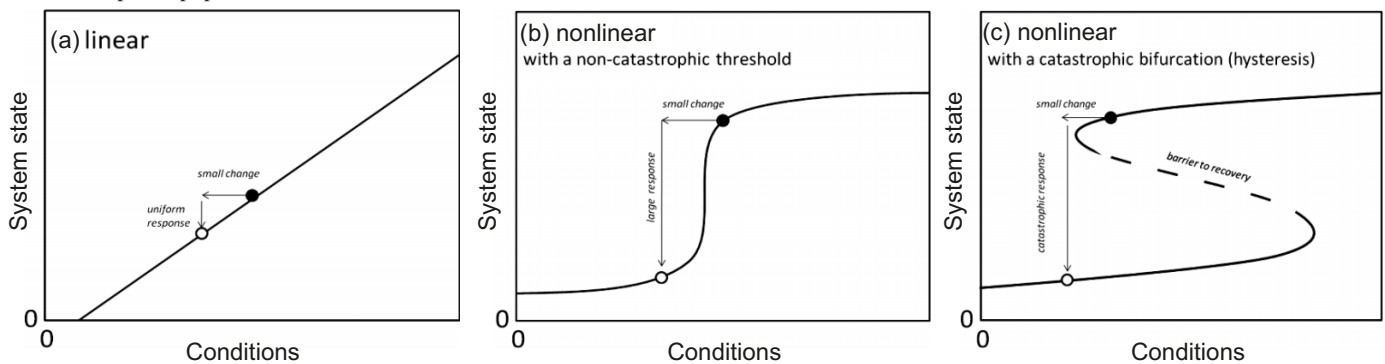
$$[4] \quad E = a_1 C + a_2 O + a_3 G + a_4 P + a_5 T$$

Field and laboratory experiments are conducted in which all factors are held constant except for the one or two factors that can be varied systematically across a realistic gradient. Jenny (1941) painstakingly explored this approach by showing how soils vary across gradients of climate on a single parent material, across different bedrock types within a single climatic region, across topographic gradients on a single type of bedrock, and so on. His intent was not to imply that state factors operate independently in real soils, but rather that more rapid scientific progress could be made if each factor were isolated in a systematic fashion.

Limits to linear, reductionist, and equilibrium thinking in a changing world

Resource professionals are trained to approach problems using reason and facts. Rational thinking, at least in the early stages of professional or technical scientific training, is typically equated with linear and reductionist thinking. In simple terms, linear thinking leads to the common sense belief that outputs from a system will be proportional to inputs (Fig. 5). For example, if half of all old growth forest within a district were converted to young plantations, linear thinking causes one to intuit that the population of old growth-dependent wildlife species in the district should be one half of what it used to be. Scientific research has repeatedly shown that relationships between wildlife populations and habitat loss can be nonlinear (Bender et al. 1998; Gibbs 1998). Critical thresholds may exist (Fig. 5b), above which an increase in the amount of old forest may cause little change, perhaps because population size is limited by predators rather than by available habitat. Conversely, if habitat availability falls below the critical threshold, populations may collapse rather than decreasing incrementally, because vital functions, behaviours and connections can no longer be maintained. Even more complex situations can arise if a fold catastrophe or bifurcation arises (Fig. 5c; Scheffer et al. 2009, more details follow). In that case restoring the habitat to its former condition will not result in a rebound of population levels, because the processes that structure the ecosystem have undergone reorganization. Rational thinking about such complex problems requires the ability to think in ways that go far beyond linear intuition or training.

Fig. 5. Three examples of how the state of a system (e.g., population size) may respond to changes in conditions (e.g., habitat availability): (a) linear relationship in which environmental change results in a proportional system response; (b) nonlinear relationship with a critical but non-catastrophic threshold; (c) nonlinear relationship with a catastrophic bifurcation. System states in (a) and (b) are reversible or resilient: as habitat availability improves, population size returns to previous level. System (c) exhibits hysteresis: when habitat availability falls below the bifurcation point, population levels fail to rebound when the habitat is restored.



Today, we have reached the limits of what can be learned through a reductionist approach. At the same time, powerful conceptual and computational tools such as cellular automata allow us to simulate eq. [2] and to conduct virtual experiments involving complex interactions that cannot be tested empirically. What has been lost over 50 years of reductionist ecology is the ability to imagine and to describe as Klinka did, what a whole, interacting ecosystem looks like. BEC supplies that missing information.

Equilibrium thinking has much in common with linear thinking and has also been pervasive in natural resources training and education. Simply put, equilibrium thinking assumes that time is reversible, that the future should be the same as the past, and that disturbed systems are set back to some prior state, then (like a pendulum) inexorably return to their pre-disturbance condition.

Today, everyone acknowledges that change is a constant. Yet equilibrium thinking underlies most models and frameworks currently in use in natural resources management. Forest growth and yield curves (e.g., Nigh 1998) are obvious examples. More insidiously, we often do not recognize the extent to which equilibrium assumptions — the Balance of Nature paradigm — condition our thinking. For example, conservation planning in BC, as elsewhere (Botkin 1992), has been based on unwritten assumptions that biota are optimally adapted to their current environment and forests were in pristine condition prior to industrial logging. In the practice of resource management it is rarely explicitly acknowledged that plant and animal populations have been in an ongoing state of flux since the melting of the continental ice sheets some 10 000 years ago (Walker and Pellatt 2008) and that just before that time, North America was ruled by spectacular megafauna including giant beavers, mammoths, and saber-toothed tigers (Ripple and Van Valkenburgh 2010). Within historic time alone, food webs in BC have experienced the Little Ice Age (Luckman 2000), the depredations of the fur trade (Innis 2001), invasion of moose (Spalding 1990), collapse of aboriginal hunter-gatherer societies, rerouting of streams, and incineration of forests associated with the gold rush (Heritage House 1987; Dickinson and Smith 1995), and so on.

The problem may not be that we expect the future to be like the past, but rather that since we cannot predict what a nonequilibrium future will look like, our default is to adopt

what we are familiar with as a base case or null hypothesis. Unlike the Tahitian navigators, our society has a profound fear of sailing forward into an unknown, unbounded future (Kauffman 2008). Do nonequilibrium dynamics imply that we cannot use the ecosystems of the present and past (i.e., the range of natural or historical variation (Landres et al. 1999)) to set resource management expectations, guidelines or standards for the future (Drever et al. 2006; Millar et al. 2007)? This question will be addressed in the sections that follow.

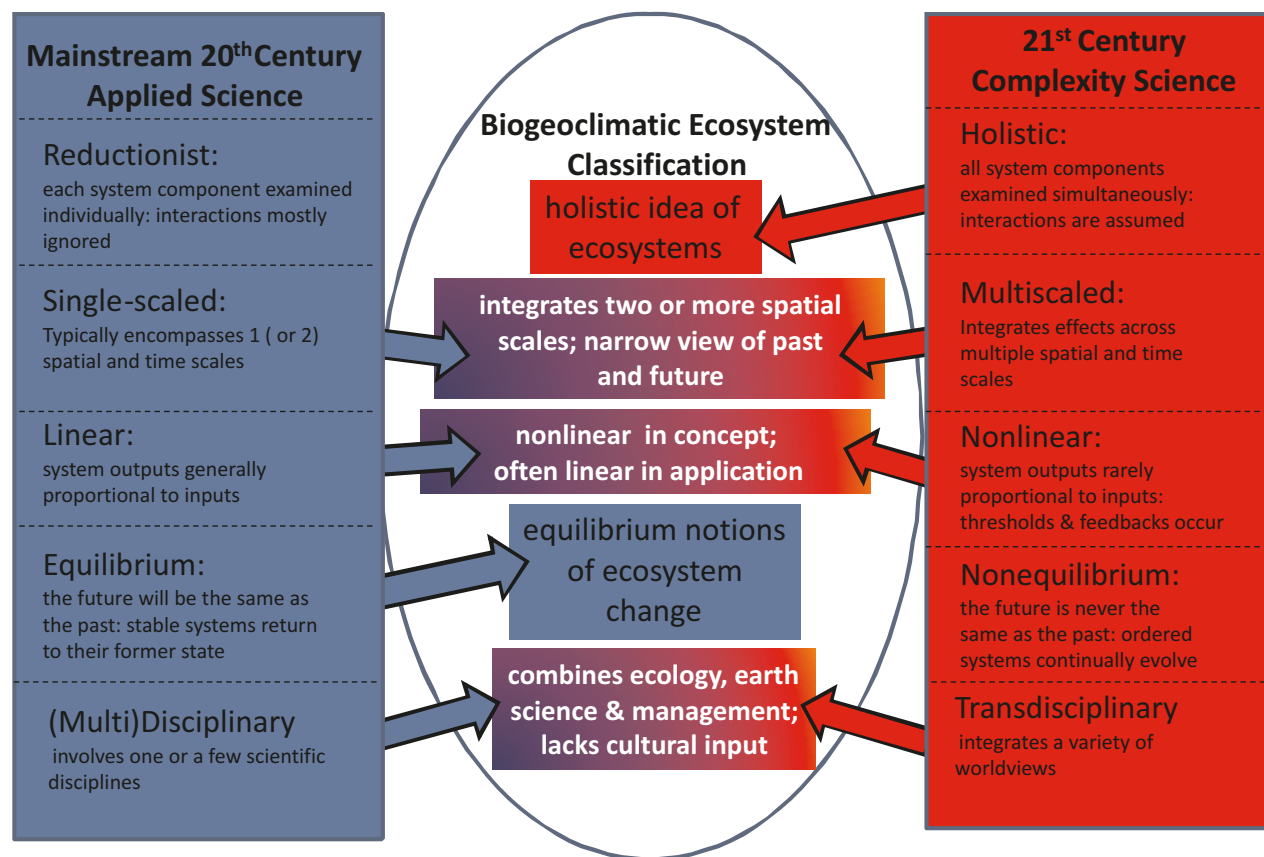
Biogeoclimatic ecosystem classification has been an essential framework that has helped resource professionals in BC to make sense of and communicate information about terrestrial ecosystems and to set guidelines for their sustainable management. If BEC is to remain functional and relevant in a nonlinear, nonequilibrium world where the consequences of global human consumption of natural resources are accelerating, the system must assist resource professionals in advancing their skills in nonlinear and nonequilibrium thinking. It absolutely should not reinforce reductionist, linear, and equilibrium notions of ecosystem dynamics. Keeping things simple for managers is not good enough.

Fortunately, the intellectual and theoretical foundations of BEC are well suited to this task. BEC is inherently holistic, multiscaled and nonlinear, though it often falls short in practical applications (Fig. 6). By adopting the new insights, language, and methods of complex systems science, it can more effectively show how nonlinearity operates in terrestrial ecosystems and can successfully transition from a dated equilibrium outlook to a contemporary nonequilibrium portrayal of ecosystem dynamics.

To summarize, there are three reasons to formally reintegrate systems theory into BEC:

1. The accelerating pace of environmental change means that a classification system that ignores the dynamic, nonequilibrium nature of ecosystems is untenable. Systems theory provides the appropriate theoretical framework for considering ecosystems as holistic, nonequilibrium systems.
2. The systems theory of the 1960 to 1980s (Odum 1983) has been upgraded into the complexity theory of the 21st century (Grimm et al. 2005; Norberg and Cumming 2008). Both the theory and computational tools are rapidly gaining the capacity needed to handle the organ-

Fig. 6. Comparing biogeoclimatic ecosystem classification to mainstream 20th century applied science and to 21st century complexity science. Within the oval, red shading shows where BEC is highly compatible with complex systems thinking, while blue indicates a need for updating.



ism- and site-specific detail that formerly could only be accommodated individually (species by species) or through a qualitative classification approach.

3. Visualization software and other digital media make it possible to translate dynamic, nonequilibrium ecosystem concepts into decision-support tools that can be comprehended by nonabstract thinkers and applied to real-world problems. It is no longer necessary to transmit information to field practitioners and managers in static, two-dimensional formats (paper maps, binary decision trees). Nonlinear decision-aids using new media will eclipse BEC if it fails to adapt.

Reframing biogeoclimatic ecosystem classification through a complex systems lens

Complex systems science applies nonlinear mathematics to a dynamical system (Bar-Yam 2003). The system can be physical, chemical, biological, ecological, social, economic, computational, neural, business, legal, or cultural. In fact, it can be any kind of system with more than two components that interact in some way. Complex systems science provides a framework for describing such systems mathematically and a suite of analytical and computational tools for modelling their dynamics. In essence, it provides the missing bridge between qualitative holistic and quantitative reductionist approaches to understanding our world.

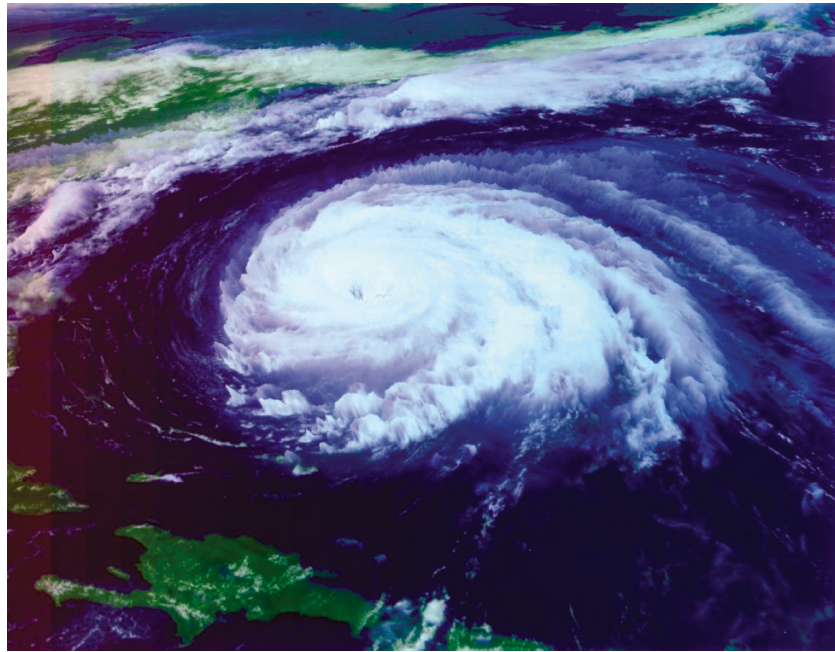
The Russian–Belgian theoretical physicist Ilya Prigogine

(1917–2003) showed mathematically for the first time how order and coherence could arise and be maintained within irreversible systems far from thermodynamic equilibrium — through self-organization (Prigogine 1978). For this work he received the Nobel Prize in 1977. The early mathematical tools to describe such behaviour were developed over the same time period as BEC began at UBC and was adopted by the Province of BC. In the intervening years, nonequilibrium mathematics and computational tools have become both more sophisticated and more accessible.

Dissipative nonequilibrium systems

The first essential concept for applying complex systems theory to ecosystem dynamics is that of a *dissipative nonequilibrium system* (Nicolis and Prigogine 1977), defined as a system far from thermodynamic equilibrium that constantly exchanges energy and matter with its environment. Prigogine worked primarily in physical and chemical environments, but it should be evident that his definition very aptly describes ecosystems. The *nonequilibrium* part of the definition means that the system is under the influence of forces that do not remain constant over time (e.g., a changing climate). The *dissipative* part means that the system is able to retain its integrity, even while its individual components — atoms, molecules, cells, organs, organisms — are being replaced. The human body is a dissipative system (with exceptional cohesiveness) because it sloughs off old cells and grows new ones while still remaining intact. A hurricane (Fig. 7) is an

Fig. 7. A hurricane is a dissipative nonequilibrium system that maintains functional integrity while constantly exchanging matter and energy with the surrounding environment (Photo: NASA, Hurricane Luis).



other example that is less cohesive and more dissipative. The notion of an ecosystem as a dissipative system that maintains its integrity while water and nutrients run in and out, while organisms die and are sequentially replaced by other species, is essential for modelling how ecosystems can simultaneously exhibit individualistic and holistic behaviour.

The second essential concept is that of an *attractor*, defined as “a set of states of a dynamic physical system toward which the system tends to evolve, regardless of the starting conditions of the system” (from the *American science heritage dictionary*. Houghton Mifflin Harcourt, Boston, Mass. p. 50). Imagine the eye of the hurricane (Fig. 7). Three salient features of the attractor should be kept in mind. First, the attractor is an endogenous or “self-organized” feature of the system that is generated by the interactions among the components of the system. It is not an exogenous or external force. There is no giant vacuum cleaner sucking the eye of the hurricane — it generates its own order and momentum. Secondly, the attractor, like the eye of the hurricane, does not have to stay in the same place to function as an attractor. Its position or parameters can shift over time. Thirdly, it is not necessary that the component parts of the system (e.g., water droplets within the rainbands of the hurricane) actually reach the attractor for the attractor to exist — rather, the system is constrained by, and tends to move toward the attractor. Put another way, the dynamics of the dissipative, nonequilibrium system are neither deterministic nor random, but are constrained nondeterministically by the attractor (Ulanowicz 2009).

From the perspective of a manager of human or natural systems, the importance of the attractor is that it sets limits to the integrity or resilience of a nonequilibrium system. By describing the attractor, it is possible to identify standards or constraints for management. These constraints are largely self-organized; that is, they arise from (cross-scale) feedbacks within the system more so than being externally forced. Human

behaviour in a civil society, to take one example, is largely constrained by individual morality, motivation, trust, and social networks, rather than being imposed through martial law.

Dynamical systems are typically described using differential equations that characterize the state of the system through time. In mathematical terms, the attractor represents the set of solutions (or limit) to those equations as the length of time (t) approaches infinity (∞).

A range of attractors are possible in nonlinear systems:

1. a **point attractor**, like the eye of the hurricane (Fig. 7), exists when the system has just one attractor. All possible starting conditions for the system tend to follow a trajectory toward a single final condition. In mathematical terms, there is a single solution (limit) to the set of equations as $t \rightarrow \infty$.
2. a **periodic attractor** or **limit cycle** occurs when the system oscillates between two attractors according to events in its trajectory. System states leading to either of the two attractors are known as **alternative states** and the critical tipping point between two domains of attraction is known as a **bifurcation** (Fig. 5). Examples of periodic attractors include the left and right swings of a pendulum, El Niño versus La Niña circulation patterns in the Pacific Ocean, and the manic versus depressive mental states experienced in bipolar disorder (Daugherty et al. 2009). Mathematically speaking, there are two possible limits for the system as $t \rightarrow \infty$, depending on the values of the input variables.
3. a **strange attractor** occurs when the trajectory of the system as $t \rightarrow \infty$ appears to be random. This is the state known as **chaos**, where the system is hypersensitive to initial conditions to the point where its trajectory over time is essentially unpredictable. Intermediate states between periodic and strange attractors, with successive bifurcations, also exist.

It should be apparent by now that attractors are a useful concept for describing the dynamics of terrestrial ecosystems. In the context of ecology, we can redefine an attractor as the set of states toward which a dynamic ecosystem tends to evolve, regardless of the starting conditions of the ecosystem. When Karel Klinka set off through the woods in search of the perfect BEC sample plot and its representative soil profile, his mind's eye was firmly fixed on that attractor.

Consider first the process of plant succession at time scales of decades to centuries on a uniform 1 ha site. The point attractor is what Clements and the BEC system refer to as the climax plant community, "a *more-or-less* permanent and final stage of a particular succession" (Clements 1936; *italics mine*). A good example are mesic, old growth forests dominated by subalpine fir and spruce, ericaceous shrubs, liverworts, and mosses with Podzolic soils that characterize moist subzones of the Engelmann Spruce – Subalpine Fir (ESSF) biogeoclimatic zone in central British Columbia (Banner et al. 1993). A periodic attractor refers to a successional process in which two alternative states are possible. For example, in the Coastal Western Hemlock (CWH) zone of northern Vancouver Island, Cedar – Hemlock and Hemlock – Amabilis fir are two alternative states or successional trajectories on mesic sites that depend on site history and nutritional status (Prescott and Weetman 1994). A strange attractor may exist when potential outcomes of a successional process are exceptionally varied, highly unpredictable, and depend almost entirely on the initial starting conditions and events that take place along the way. Imagine 10 vacant lots with similar soils scattered across the city of Vancouver that are fenced off and left alone. Will they converge on the same successional trajectory? Or will it depend on the biological starting conditions, where the local crows prefer to forage, and whether there is a native park or a row of urban shade trees nearby? The principles of BEC were not intended to apply to the chaotic environment of a modern city, but this illustrates my point. At some stage of environmental complexity the notion of a point attractor or deterministic climax ecosystem loses its utility. There are likely to be examples, notably in grasslands, alpine tundra or in species-rich forests with complex disturbance regimes where the attractors lie closer to chaotic than periodic.

The examples in the previous text differ in their degree of predictability. If I am brought to each site blindfolded and told that it is an east-facing zonal site (Fig. 3) with loamy soils, 20% slope, and glacial till parent materials that has not experienced a stand-destroying disturbance for 300 years, with what degree of certainty can I predict the plant community and soils around me when I remove the blindfold? In the case of the Engelmann Spruce – Subalpine Fir point attractor, I can be virtually 100% certain that my stand will be dominated by subalpine fir, with spruce scattered on tip-up mounds, an Ericaceous shrub-dominated understory with a few small patches of subalpine forbs, and mix of *Dicranum*, feathermosses and *Barbilophozia* liverworts on a mor humus over Podzol. For the CWH periodic attractor, I can be 100% certain that it will be either the Cedar–Hemlock or Hemlock–Amabilis fir state, but cannot predict which of the two possibilities it will be. In the urban ecosystem example, the amount of prior knowledge regarding on-site conditions and the surrounding neighbourhood required to reasonably pre-

dict potential ecosystem conditions may make this a futile exercise.

The BEC guidebooks have dealt with alternative successional trajectories by defining the climax association as dominated by shade-tolerant coniferous trees and treating other possibilities, such as long-lived forests dominated by broad-leaved trees as "seral associations" (Williams et al. 2001) or "seral ecosystem units" (DeLong 1988). The possibility that fundamentally different soil and vegetation processes and ecosystem conditions may result from alternative disturbance regimes and consequent developmental trajectories (Bergeron 1991; Wardle et al. 1997; Jasinski and Payette 2005) is not addressed. A priority for updating BEC will be to formally recognize the existence of multiple ecosystem states (Tausch et al. 1993; Scheffer et al. 2001; Campbell et al. 2009) and to describe examples for varied biogeoclimatic zones. Another priority will be to consider where new bifurcations may result from global change drivers such as climate, habitat fragmentation, nutrients, and invasive species.

Fast and slow variables

In the context of ecosystem classification, the dynamics of plant succession take place over relatively short time scales and can be described as "fast" variables (Carpenter and Turner 2000). Slow variables such as soil-forming and geological processes that take place over thousands to millions of years are also influenced by point, periodic and strange attractors (Phillips 2003). For example, over much of the CWH biogeoclimatic zone, the development of a Podzolic soil profile functions as a long-term point attractor for the ecosystem at site (mesic) and landscape (zonal) scales. Banner et al. (1983) showed, however, that in cool, very wet, maritime CWH subzones where humus accumulations are thicker, the attractor can oscillate periodically from a moderately well drained upland forest soil (Folisol or Folisolic Podzol) to a saturated bog woodland soil (Humisol) in response to shifting climate and associated changes in internal soil drainage. Strange (chaotic) attractors in soils have been described to explain large and apparently random variability in soil profile development observed across smaller spatial scales (Phillips et al. 1996). Soils on a given surface will tend to become increasingly variable with time, even if subject to the same suite of pedogenic factors and exogenous inputs, because minor perturbations grow and emerge into complex spatial patterns (Schaetzl et al. 2006).

An important contribution of nonequilibrium theory to understanding the process of soil formation is the notion that attractors can shift over time in response to changes in climate, vegetation cover, or rates of erosion and deposition, so that soil profiles continuously evolve, developing in one direction for a period of time, then changing directions or surpassing intrinsic thresholds, rather than developing unidirectionally towards an equilibrium state of mature soil development (Johnson et al. 1990; Huggett 1998). This phenomenon of shifting attractors is particularly important in ecotonal areas that represent zones of climatic, edaphic or vegetation transition or tension. In such areas a small change in an external driver may result in a disproportionately large shift in soil processes when reinforced by a positive feedback loop. Alternatively, compensating or oscillating environmental factors (i.e., a negative feedback loop) may prevent the

Table 2. Tools and techniques used in complex systems science (adapted from Haeussler and Thorpe 2010).

Technique	References
Agent-based models	Axelrod 1997; Gilbert and Terna 2000; Bonabeau 2002
Cellular automata	Wolfram 1986, 2002
Data mining	Kantardzic 2003
Adaptive (fitness) landscape models	Wright 1932; Kauffman 1995; Gavrillets 2004
Fuzzy logic	Hajek 1998; Berkes and Berkes 2009
Game theory	Rasmusen 2006; Shoham and Leyton-Brown 2009
Information theory	Shannon 1942; Cover and Thomas 2006
Machine learning	Alpaydin 2004
Network analysis	Barabasi 2002; Newman 2003; Durrett 2006; Knoke and Yang 2008
Neural networks	Bar-Yam 2003
Nonlinear equations	Dennis and Schnabel 1996; Khalil 2001
Statistical mechanics	McQuarrie 2000; Evans and Morriss 2008
Symbolic dynamics	Lind and Marcus 1995; Williams 2004

soil forming processes from coming too strongly under the influence of any particular attractor for any length of time.

In summary, vegetation succession and soil profile development toward attractors are important emergent properties of terrestrial ecosystems that underlie BEC. Describing these attractors, and the basin of attraction (or state space) defined by an attractor, is the essence of ecosystem classification. But succession and soil formation are perpetually dynamic processes that shift or adapt to changing circumstances rather than deterministically approaching a stable equilibrium. Ecosystem classification should, therefore, evolve naturally from a static, descriptive procedure to a dynamic modeling exercise (Prentice et al. 1992) that will allow users of the BEC system to project and “hindcast” (Walker and Pellatt 2008) terrestrial ecosystem development through time. The next section will outline how that evolution can take place.

Alternatives to linear, equilibrium modelling

Complex systems tools and techniques

Complex systems science uses a variety of analytical tools for dynamic, nonequilibrium, nonlinear modelling that could productively be applied to BEC (Table 2). These tools are not exclusively used for whole-system modelling. They also have applications in more reductionist settings. One of the reasons why convergence between holistic and reductionist approaches to understanding ecosystem dynamics is rapidly taking place is that as systems models have become less general and reductionist models have become more complex, the two approaches have begun to converge, using similar analytical tools to solve similar problems.

The internet has revealed that many techniques employed by ecologists have long been in use in other domains using different terminology and different software. A famous example is the Shannon Index (also known as the Shannon-Weaver or Shannon-Wiener index) used in ecology as a measure of species diversity (Pielou 1975; Spellerberg and Fedor 2003). This formula, known in physics as Shannon’s entropy, was originally developed by Claude Shannon (1916–2001), the founder of information theory (Table 2), during World War II as a means of distinguishing radio signals from noise over crackly communication lines (Shannon 1942).

In the following sections, I illustrate how two techniques from Table 2, adaptive or fitness landscape modelling and agent-based modelling, can help to transform BEC from a

static, equilibrium model of ecosystem description to a non-equilibrium model of ecosystem dynamics.

Example 1. Using adaptive landscapes to model shifting ecosystem attractors

The concept of an adaptive or fitness landscape arose more than 50 years ago in genetics and evolutionary biology (Wright 1932; Simpson 1944), but came into global prominence through the writings of Stuart Kauffman (Kauffman and Levin 1987; Kauffman 1995), a pioneer of complex systems science.

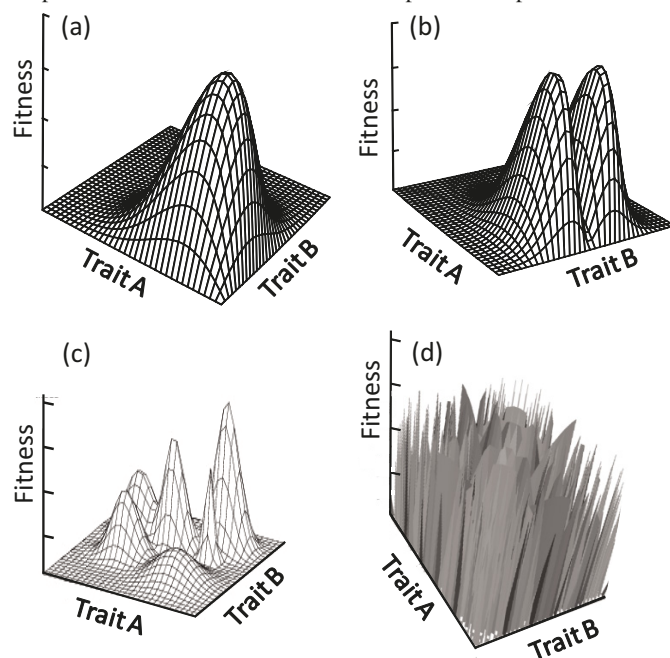
The original focus of research was on the process of evolution in an unchanging selective environment, referred to as a stationary landscape. More recent developments have focused on the evolution of the landscape itself (Arnold et al. 2001). This shift in thinking from a stationary to a moving model of the landscape is relevant to the conceptual evolution of BEC towards a dynamic, nonequilibrium system.

In its simplest version, the adaptive landscape (Fig. 8) can be imagined as a two-dimensional space that represents all possible combinations of two phenotypic characters. Elevation contours on the space (the third dimension) represent population fitness or adaptiveness. In theory, the landscape can consist of any number (*n*) of characters, translating into an *n* + 1 dimensional hyperspace, but it is easiest to visualize it with *n* = 2 characters and *n* + 1 = 3 dimensions. Peaks in the landscape represent attractors, as defined previously. These are the genetic combinations with the highest fitness, and thus a population will tend to evolve towards individuals possessing those traits, since those individuals will produce the most offspring. For any set of traits, there may be one or more combinations that lead to improved fitness. A smooth landscape with a single peak has a point attractor (Fig. 8a), but it is also possible to have two peaks (periodic attractors; Fig. 8b) or many peaks (multiple attractors) in a rugged or complex landscape (Fig. 8c).

An essential idea for understanding adaptive landscapes with more than one peak is that a subset of the population will evolve towards a local peak that is not as tall as the highest peak in the landscape and will become trapped there, because within their local neighbourhood the smaller peak represents a fitter alternative than their prior state. This is one way in which genetic diversity is maintained within a population even though not all combinations of genetic traits are optimally fit. Such movement of the system toward a lo-

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Fig. 8. Adaptive or fitness landscape model used as an abstract representation of the process of evolution. The *x* and *y* axes represent two genetic traits. The vertical dimension (*z* axis) represents the fitness of individuals possessing those traits. Possibilities include (a) smooth landscape with a single peak or point attractor; (b) two peaks (periodic attractors); (c) a rugged or complex landscape with many local fitness peaks; or (d) a chaotic, rapidly changing landscape in which no combination of traits provides superior fitness.



cal, rather than global, optimum is a characteristic feature of many complex systems, including terrestrial ecosystems.

So far we have visualized a static landscape in which the circumstances that determine fitness do not change. If however, the local environment changes, a different combination of traits are likely to have superior fitness under the new environmental conditions. In that case the fitness peaks will begin to shift, causing the surface of the landscape to ripple and deform. Several peaks might merge, and new higher or lower peaks may form. If the rate of change in the environment is so rapid that evolution toward a stable combination of superior traits is no longer possible (i.e., each generation faces new conditions and tends to evolve in a slightly different direction), the landscape is deemed to have become chaotic (Fig. 8d).

Ecosystems are prototypical examples of complex adaptive systems (Levin 1998). Unlike a population of organisms, they do not engage in a Darwinian process of selective reproduction, but the concept of an adaptive landscape, with appropriate modifications, can nonetheless be applied to an ecological landscape. Similar, though not identical, mathematical approaches can be taken to model the changes that occur in response to environmental change.

To visualize how this applies to BEC, think of the edatopic grid (Fig. 9a). The edatopic grid represents an abstract landscape that encompasses all possible combinations of moisture and nutrient availability within a region of homogenous climate. This is not a real landscape, but if the reader is able to conceptualize an edatopic grid and translate the information it contains to a concrete physical landscape such as a river val-

ley, then the notion of an adaptive ecological landscape should not require a great leap in abstract thinking.

Now imagine a third dimension to the edatopic surface that is analogous to the fitness gradient in the evolutionary landscape (Fig. 8). Contours on this surface do not represent topography. Instead they represent the degree of internal organization (or information content) in the ecosystem (Ulanowicz 2009), which can be crudely estimated by empirical indices such as ecosystem carbon storage or the age of the system since the last major disturbance. Peaks in the landscape are the ecological attractors — defined once again as the set of states toward which a dynamic ecosystem tends to evolve, regardless of the starting conditions of the ecosystem. In Clementsian terms, peaks represent climax or disclimax plant communities with mature soil profile development.

Low points in the landscape have high entropy and represent recently disturbed ecosystems, with minimal carbon storage, pioneering plant, animal, and microbial communities, high amounts of available, unutilized resources, and high rates of leakage or erosion. In essence, the third axis of our modified edatopic grid is a measure of ecosystem complexity.

From a low point in the landscape, succession or soil formation can proceed in several directions depending on the number of local peaks. This is a departure from the current state of BEC that allows a single successional trajectory for a given location on the edatopic grid. Admittedly, succession will be constrained by inherent site quality (soil moisture regime, soil nutrient regime). It is not possible for a riparian forest ecosystem with giant cottonwood trees and waist-high ferns to develop on a dry rocky ridgetop, but there is a degree of stochasticity (which plants and animals first arrive at the site), plasticity, and contingency to the outcomes that is not reflected within the deterministic confines of BEC. Some early BEC guidebooks (e.g., Yole et al. 1989) used overlapping ovals to delineate site series, so as to indicate several possible successional trajectories for a single combination of soil moisture and soil nutrient availability (Fig. 9b), but overlaps were subsequently removed (e.g., Banner et al. 1993) in favour of a modernized model with less ambiguity (Fig. 9c). It is now time for BEC to evolve from streamlined and modern, to greater complexity.

Instead of overlapping circles, the adaptive landscape model allows a system that starts off at a low point in the landscape after disturbance to follow a successional trajectory uphill in one or more directions (Fig. 10), depending on the severity and size of the disturbance and on events that precede (e.g., a prior hot burn) or follow (e.g., an excellent spruce seed year; Parminter 1983). Some moisture and nutrient combinations have a greater variety of possible successional trajectories than others. Sites located midway between two or more periodic attractors are most likely to have multiple potential successional trajectories, whereas those situated directly beneath a strong attractor are likely to repeatedly follow the same trajectory.

What happens to the BEC adaptive landscape when the climate changes? Under the existing framework, each edatopic grid represents the range of site series present under uniform unchanging climate. To predict what might happen as the climate changes, one can flip to another chapter or open another guidebook and locate the grid for a slightly warmer, drier or wetter climate. For example, the moist cold

Fig. 9. The edatopic grid used in biogeoclimatic ecosystem classification: (a) soil nutrient and soil nutrient regimes on x and y axes; (b) distribution of site units across an Engelmann Spruce – Subalpine Fir (ESSF) landscape (Yole et al. 1989, with permission); (c) the same ESSF landscape depicted by Banner et al. (1993, with permission).

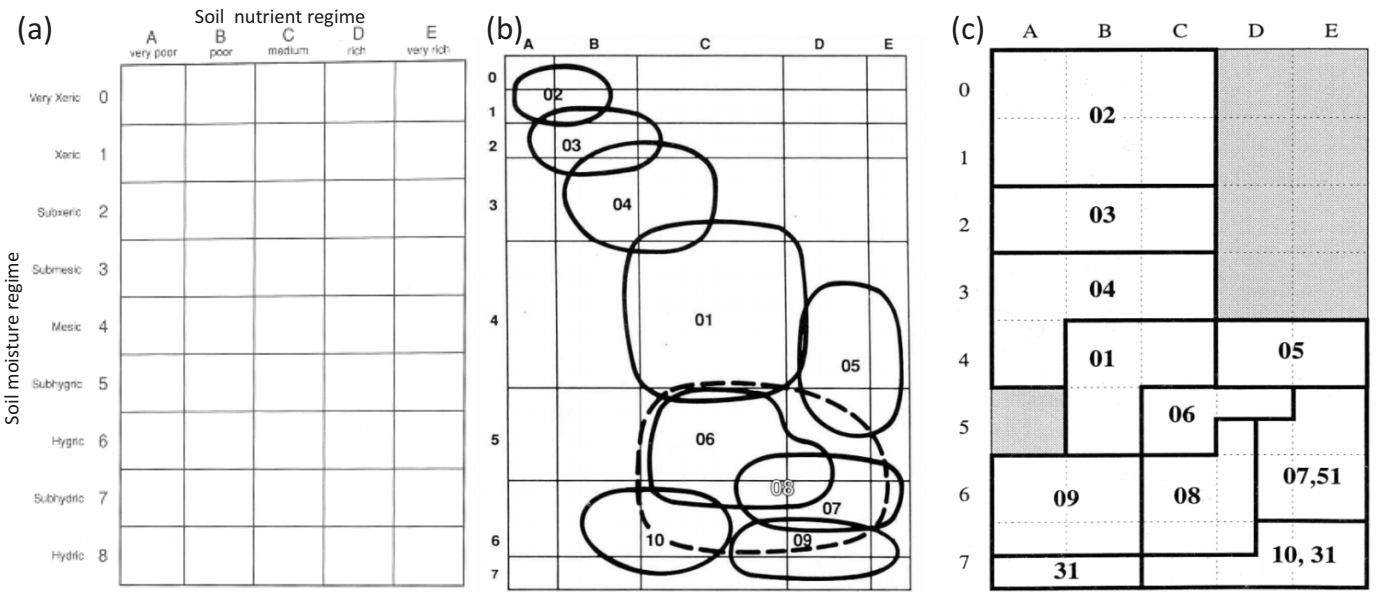
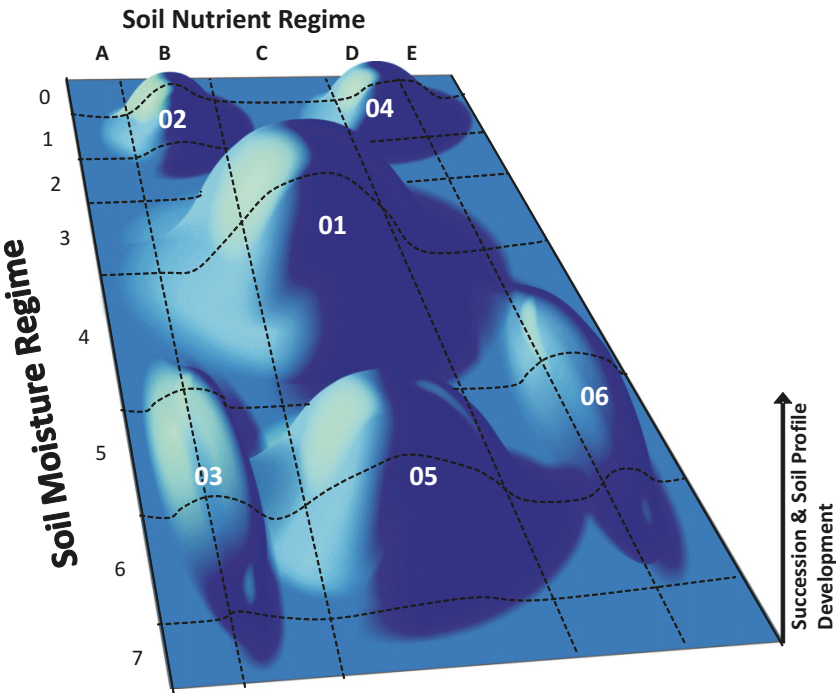


Fig. 10. The edatopic grid reconceptualised as a dynamic adaptive landscape with multiple shifting ecosystem attractors. The vertical dimension (z axis) represents the degree of self-organization resulting from succession and soil profile development and is a measure of ecosystem complexity (Illustration: H. Saefkow).



Engelmann Spruce – Subalpine Fir Subzone (ESSFmc) might transition into something like the moist cool Engelmann Spruce – Subalpine Fir Subzone (ESSFmk) by 2030, like the dry warm ESSFdw by 2050, and like the dry warm SubBoreal Spruce (SBSdw) subzone by 2070. One can visualize this predicted trajectory by juxtaposing their respective edatopic grids (Fig. 9c) in a guidebook, then thumbing rapidly through the pages to create an animated image. Under this scheme, the climate envelope shifts and ecosystems move to-

wards equilibrium with the new climate (Hamann and Wang 2006). Soil moisture and nutrient regimes remain essentially fixed because they are a function of topography and parent materials and thus independent of climate.

Under the adaptive landscape model the process of change is conspicuously less linear and does not rest on an assumption of potential vegetation in equilibrium with climate. When a threshold or bifurcation is crossed, the ecosystem shifts from one attractor to another. This could result from

short- or long-term climatic stress including extreme weather events, from a single or multiple disturbances such as beetle attack, wildfire or chronic overgrazing, the arrival of new species, air or water pollution, or any changing combination of these factors. An ecosystem can potentially shift back and forth between or among several attractors for an extended period of time (as in Banner et al. 1983). While BEC assumes that shade tolerant coniferous trees eventually replace intolerant pioneer species and nutrient-demanding ruderal species are quickly replaced by stress-tolerant understory plants as forest succession proceeds, this may not happen with multiple stressors or pervasive small scale disturbance (e.g., Hibbs and Bower 2001; Axelson et al. 2009). Alternatively, a landscape that was formerly rugged, with multiple competing attractors could transform into a smoother homogenized landscape with a single dominant attractor, as has been documented in eastern North America (Schulte et al. 2007; Nowacki and Abrams 2008) and Mediterranean Europe (Lloret et al. 2002; Clavero and Brotons 2010).

Adaptive landscape modelling allows users to tune parameters and conduct sensitivity analyses to examine successional outcomes under a range of disturbance and stress scenarios. The user can explore, rather than predict, possible futures within a familiar BEC framework. Adaptive landscape modelling is an abstract, aspatial modelling approach that helps to identify ecosystem attractors and visualize complex successional and soil formation trajectories. It represents a multi-dimensional dynamic replacement for the static edaphic grid.

Example 2. Agent-based modelling for predictive ecosystem mapping under nonequilibrium conditions

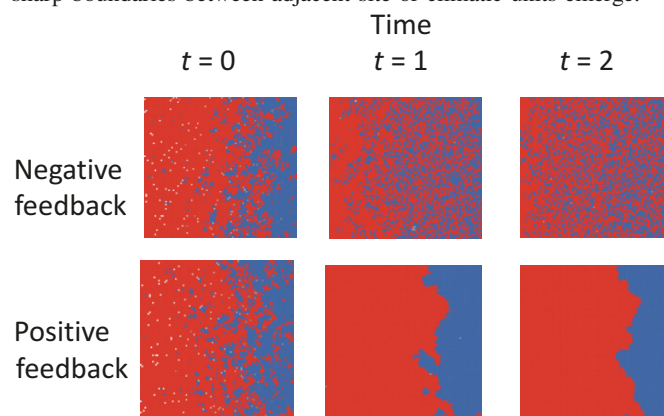
This second example describes a spatial modelling framework that simulates successional and soil formation trajectories. Its purpose is to explore how spatial patterns across landscapes evolve over time. It could serve as a dynamical alternative to predictive ecosystem mapping (Meidinger et al. 2000; MacMillan et al. 2007).

As described earlier, complex systems science has shown that much of the order or pattern that exists in the world results from local-level (endogenous) interactions among the components or “agents” in a system, rather than being dictated by exogenous factors or forces. The phenomenon of system-wide behaviour or pattern resulting from the actions of individual, autonomous agents is known as self-organization or emergence (Nicolis and Prigogine 1977; Kauffman 1993). Agent-based, or individual-based, modelling is a computational approach that generates self-organizing or emergent behaviour by allowing each agent in the model to interact with other autonomous agents (DeAngelis and Gross 1992).

Individual-based forest models such SORTIE-ND (Astrup et al. 2008) are agent-based models in which the growth of a tree is influenced by the trees that surround it. While it is easy to grasp the concept of an organism such as a tree, or an animal acting as an autonomous agent in a model and interacting with surrounding trees or animals in the same population, the idea of a terrestrial ecosystem as an autonomous agent that interacts with surrounding ecosystems is more difficult to grasp, especially for those with an individualistic rather than a holistic conception of an ecosystem.

In raster-based spatial landscape models developed using

Fig. 11. An agent-based ecosystem distribution model that explores consequences of changes in climate, disturbance regimes and self-organizing feedbacks at the site or zonal (climate) level. Each cell (agent) in the model represents a unit of land under the influence of a single ecosystem attractor (red or blue). At the site level, the grain of the model is approximately twice the height of mature vegetation and each cell has uniform soils. At the zonal level, the spatial scale of the model is on the order of 1 km per cell with each cell representing zonal site conditions. With negative plant-soil feedbacks the landscape becomes homogenized over time; with positive feedbacks sharp boundaries between adjacent site or climatic units emerge.

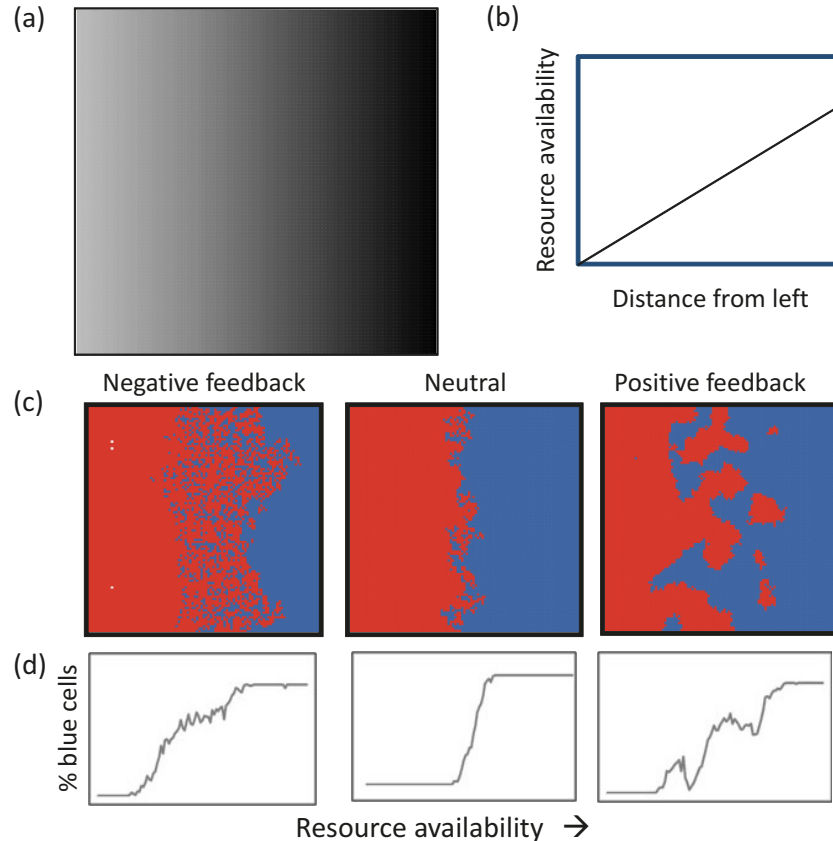


the LANDIS (Mladenhoff 2004) or SELES platforms (Fall and Fall 2001), the individual agents are stands of uniform tree age and species composition. Adjacent stands interact with one another by influencing processes such as the spread of fires, insects or tree seeds or the economic efficiency of logging operations. Fundamental ecosystem properties that influence BEC site classification, such as moisture and nutrient status, topography and parent materials are usually not considered in detail or assumed to be enduring, unchanging stand features that do not actively influence neighbouring stands.

There is room between tree-and-gap models such as SORTIE-ND and stand-to-landscape models developed with SELES or LANDIS, for ecosystem-level agent-based models that operate at an intermediate spatial scale (Figs. 11 and 12). Such models can be used to explore how the pattern of BEC site units within a landscape might change in a warming climate. Larger grain sizes with modified assumptions could model how the regional pattern of BEC zones, subzones and variants changes over time.

At the site level, the grain of the model is approximately twice the height of mature vegetation and each cell has uniform soils. Imagine that blue cells (Figs. 11 and 12) are under the influence of a mesic attractor (e.g., a typical moist, cool SubBoreal Spruce site unit such as the Spruce–Huckleberry–Highbush cranberry site series (SBSmk/01; DeLong et al. 1993)). Red areas are under the influence of a xeric attractor (e.g., Lodgepole pine – Cladina – Step moss site series (SBSmk/02)). Areas that are an undifferentiated mix of red and blue cells would be classified as submesic to subxeric (e.g., Lodgepole pine – Feathermoss – Cladina (SBSmk/03)) and, like the overlapping circles in Fig. 9b, will shift toward the xeric attractor with an increased frequency of disturbance that incinerates humus layers and kills shade tolerant trees and toward the mesic attractor under a disturbance regime that favours humus accumulation and regeneration of shade

Fig. 12. Nonlinear changes in ecosystem states across a resource gradient. The red state is favoured at low resource levels, the blue state at high levels. (a) Resource availability in the agent-based model increases across the horizontal axis, with darker grey tones indicating higher resource availability. Although the resource gradient is linear (b), the distribution of red and blue states is nonlinear (c–d). With negative plant–soil feedback (left), there is a well-defined intermediate zone. With no feedback (centre), a sharp threshold develops. With positive feedback (right) the system exhibits hysteresis (Fig. 2c), whereby red patches persist at resource levels that favour the blue state, but once gone cannot be restored.



tolerant species (Sulyma and Coxson 2001; Jasinski and Payette 2005).

At the zonal level, the spatial scale of the model is on the order of 1 km per cell with each cell representing zonal site conditions. Imagine now that the blue cells are under the influence of a CWH attractor (zonal sites have Podzolic soils and are dominated by western hemlock) while red cells are under the influence of an SBS attractor (zonal sites have Luvisolic soils and are dominated by a mix of white spruce and subalpine fir). Areas that are an indeterminate mix of red and blue cells would be classified as Interior Cedar–Hemlock zone (Meidinger and Pojar 1991), and resemble the CWH zone where disturbance cycles are long, or the SBS zone if disturbance cycles are shorter.

Transitions from the red to blue state will depend on the nature of internal plant–soil–disturbance feedbacks. Although exogenous factors are identical in each scenario, with negative feedbacks (a weak, vascillating attractor) the landscape gradually becomes homogenized or intermediate in character, whereas with neutral or positive feedback, sharp ecosystem boundaries emerge (Fig. 11 (right hand panels); Fig. 12c). Strong positive feedback allows islands of red to persist out of equilibrium with prevailing environmental conditions.

Although BEC recognizes that organisms modify their own environment, this information is rarely used to classify a site or to predict what kind of ecosystem might be found

at a particular spot in the landscape. The system works well where strong climatic and topographic gradients override the influence of disturbance and endogenous factors plant, soil, and zootic feedbacks. It does not work particularly well where climatic and topographic gradients are weak (e.g., east of the Rocky Mountains) or where disturbance regimes are independent of climatic gradients (e.g., Bergeron 1991).

Under an agent-based modelling framework, exogenous factors such as climate, parent materials, topography, and large scale disturbance are used to structure the model, but there is also an explicit role for self-organizing plant–soil feedbacks including neighbourhood tree-to-tree interactions. An important difference between an agent-based modelling framework and predictive ecosystem models (Meidinger et al. 2000) is that the behaviour of an agent or patch on the landscape is influenced by the character and behaviour of surrounding agents. A small patch of lichen woodland surrounded by mesic forest, for example, will respond differently to environmental change than a one within matrix of lichen woodland. Another difference is that plant, soil, or zootic feedback mechanisms within the patch itself affect both the resistance of the patch to change and its resilience after disturbance. Under traditional BEC frameworks, what matters are the physical attributes of the site and the abiotic forces imposed upon it.

Current ecosystem distribution models based on BEC,

such as the bioclimatic envelope modelling of Hamann and Wang (2006), define the end point of a trajectory of vegetation change based on ecosystems reaching equilibrium with the new climatic conditions. This process of forest, grassland, and tundra vegetation and soils approaching the new equilibrium will take centuries to millennia (Walker and Pellatt 2008) over which time the climate will continue to change (hopefully at a slower pace) while species distributions and disturbance regimes undergo additional changes that are not directly climate-driven. As we saw in Example 1, a more realistic view is that of vegetation zones shifting and mutating under the influence of constantly moving attractors. The changes will not proceed linearly, with plants, animals, microorganisms, and soil profiles marching north and up mountain slopes in lock-step with changing temperature and precipitation regimes. There is likely to be an unbalanced mix of linear, threshold, and bifurcation changes (Fig. 5) occurring at varied rates across levels of biological organization and spatial scales. The panarchy model of nested adaptive cycles (Gunderson and Holling 2002) more effectively portrays the cross-scale transformations that ecosystems are likely to undergo than a series of sequential bioclimatic envelopes.

Although the BEC system provides a basis for imagining ecosystems as autonomous agents capable of self-organizing behaviour, the bioclimatic envelope models of Hamann and Wang (2006) and Schneider et al. (2009) model only the top-down effects of exogenous environmental factors (climate, wildfires). These approaches are a logical step-by-step process for increasing model complexity, but will not provide realistic portrayals of ecosystem response to changing climates until they also factor in the site-level plant-soil feedback processes (Ehrenfeld et al. 2005; Rietkerk and van der Koppel 2007) that underlie ecological resistance and resilience. Agent-based modelling can complement both the modified bioclimate envelope approach to ecosystem change (Schneider et al. 2009) and mechanistic approaches that model climate responses of tree species individually (Nitschke and Innes 2008; Coops et al. 2010).

These two examples of nonlinear modelling are in the conceptual stage and will require considerable additional work to become operational. They can, however, be immediately introduced into BEC training and climate change adaptation workshops as visualization aids to assist students and resource professionals in learning about nonlinear dynamics within a familiar BEC context, including concepts such as alternative states or multiple domains of attraction and regime shifts that can affect forest and rangeland succession in systems influenced by multiple drivers of change (Scheffer et al. 2009).

Biogeoclimatic ecosystem classification as a complex adaptive system

Institutional adaptation

This review has focused on applying complex systems theory to the scientific and technical attributes of BEC, but the point must be made that an adaptive systems approach can also be employed to address the delivery of the BEC program and its use in resource management decision-making — in essence, the integration of social and ecological systems (Berkes et al. 2008; Chapin et al. 2009). The BEC program itself should be viewed as a robust complex adaptive system

rather than as a static monolith. One straightforward example of increasing adaptiveness would be to give users more flexibility to modify and adapt the learning tools and decision-aids to suit their own needs. A collaborative approach to decision-making and adaptability to new problems facing provincial land and resource managers have been strengths that allowed the BEC program to retain the support of government and users from the 1970s to the 2000s (Table 1); but real, institutional adaptation means not resting on one's laurels.

Viewed in an optimistic light, the dismantling of the British Columbia Forest Service research program (Parfitt 2010) could serve as the external "shock" that initiates a much-needed cycle of experimentation and adaptive renewal (Berkes et al. 2008). An important component of this renewal will be to raise the profile of BEC within the academic ecology, earth science, and global change communities. This can best be done by demonstrating the compatibility between holistic ecosystem classification and the nonlinear conceptual frameworks and simulation models increasingly employed in these disciplines (Walker and Salt 2006; Berkes et al. 2008; Campbell et al. 2009; Chapin et al. 2009; Scheffer et al. 2009).

The following are some process-based and content-based recommendations for adapting BEC to the rapidly changing, post-modern environment of the 21st Century.

Process-based solutions

BEC needs to excite and enlighten a new generation of scientists and resource professionals. To do so, it must:

- Incorporate dynamic, non-equilibrium concepts into BEC training materials and introduce them into classrooms and field training session.
- Harness the skills of the tech-savvy generation and use new, interactive media to replace static two-way grids, decision trees, and guidebooks.
- Entice field-oriented and technologically inclined students to work together through programs such as the MITACS Accelerate internship in mathematics of information technology and complex systems (www.mitacs.ca). In this *century of ecology* (John Todd, cited p. 60 in Kumar and Whitefield 2007), talented youth should be engaged in the mathematical challenges of planetary stewardship (Power and Chapin 2009) rather than designing disposable tech toys.
- Provide universities with financial incentives to participate BEC renewal by, for example, funding graduate scholarships and formally incorporating BEC renewal into government-university collaborations. This will be especially important if the downsizing of government research capacity continues.
- Invest in a mentorship program to train a new generation of master BEC practitioners who can integrate field ecology with earth sciences in the tradition of Karel Klinka and the Tahitian navigators.

Content-based solutions

BEC program materials and web-based content must:

- Shift from static or equilibrium descriptions of current baseline conditions to a dynamic, nonequilibrium visualization of alternative futures.
- Place less emphasis on classifying and prescribing, and more emphasis on understanding, interpretation and adaptation, making use of simulation modeling, to equip resource pro-

fessionals with better decision-making skills in an uncertain future.

- Focus more attention on local scale, bottom-up ecosystem responses to global change. Models must address catastrophic and noncatastrophic change at the site level (plant–soil–disturbance feedbacks) as well as at the climate level (climatic envelopes). In the field, site diagnosis should receive equal or greater priority than mapping.
- Pay attention to state transitions in slow-changing variables (soils, geology, biogeochemical cycling) as well as fast-changing variables (plants, pests, wildlife, humus, peak flows).
- Consider multiple temporal scales as well as spatial scales. BEC should formally incorporate paleoenvironmental and dendrochronological information into its databases and extension products. Bioclimatic envelope projections (Hammann and Wang 2006) should include “hindcasting” (Hebda 1995; Walker and Pellatt 2008) as well as forward simulations of the distribution of biogeoclimatic units over time for continuity and to illustrate the accelerating pace of change.
- Incorporate human ecology into BEC by making a formal transition from the management of “natural” ecosystems to the management of social–ecological systems (Berkes et al. 2008). It is time to eschew the artificial separation of the natural and the human-made. Effects of aboriginal, historical and present-day land use practices on disturbance regimes, species, soils, and ecosystem distributions should be recognized and further studied. Modelling the composition, structure, and dynamics of urban ecosystems (McDonnell et al. 1997; De Kimpe and Morel 2000; Alberti et al. 2003) within a BEC framework can serve as a test case for integrating nonequilibrium and complex adaptive systems theory into ecosystem classification.

Conclusions

Ecosystems respond both individualistically (species by species) and holistically (system-wide development) to changes in resource availability, disturbance, and species distributions. Although the species-by-species response behaviour of ecosystems often appears to be dominant over system-wide developmental responses, their full behaviour cannot be adequately comprehended — let alone predicted — without taking this dualistic nature into account. Complex systems models that approach terrestrial ecosystems as dissipative, nonequilibrium systems with both individualistic and systemic attributes are needed to model the emergent behaviour resulting from interactions among ecological drivers such as climate change, land use change, disturbance regimes, and invasive species.

Biogeoclimatic ecosystem classification takes an integrative, nonlinear approach to ecosystems that includes both top-down (climate level) and bottom-up (site level) drivers. Resource practitioners using the system thus have a head start in understanding and modelling whole system responses, compared to those with reductionist or single-discipline understanding of population or environmental dynamics and no widely used ecological land classification system to underpin ecosystem management. BEC will, however, quickly become obsolete unless it updates from a static, de-

terministic description of climax ecosystems to a dynamic, nonequilibrium view based on shifting ecosystem attractors.

It is well worth the effort to invest in engaging a new generation of scientists and resource professionals in the renewal of BEC for both scholarly and practical reasons. A key component of the renewal effort must be field apprenticeships like those engaged in by the Tahitian wayfinders (Davis 2009) and early BEC-masters to give young ecologists and earth scientists the skills and sensory capacity to integrate plants, animals, soils, and atmosphere into a holistic knowledge of ecosystems. Advanced modelling and graphical techniques should be applied to ecosystem classification datasets and training materials. For scholars, the payoff from joining up the venerable Old World tradition of natural science with emerging nonlinear technologies is that it will deliver surprising new insights into ecosystem behaviour. The value for practitioners lies in its potential to proactively improve land and resources management.

Ongoing changes to BEC to incorporate new scientific insights are fundamental to treating the BEC program itself as a complex adaptive system. The real challenge for institutional reform, however, will be to find ways to use the scientific insights provided by a renewed BEC program to revolutionize the relationship between society and the living land.

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