

SELF-SUSTAINING FOREST

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Abstract. It has been recognized and discussed in the literature that values associated with forest integrity, i.e., sustainability and diversity, are relevant to the three aspects of self-organisation: resilience, health, and evolvability. However, evolvability has not yet been studied and also there is still no relevant notion of forest health. This calls for a biodynamic approach to forests and clearly addresses questions relating to scaling and self-organisation since the different levels of detail must be compatible to ensure the consistency of sustainability and diversity assessments. To support the development of a biodynamic approach to forests we review the concepts of self-organisation, criticality and resilience, and their relationship to forest integrity in the light of fractal organisation theory. An exploration of fractal connectivity behind key bioindicators and biomonitors in the avoidance of a biodiversity threshold can be suggested thus far. Forest integrity refers to empirical scaling relationships that are emergent features of biodiversity. In a forest, species as different as fungi, plants, animals and insects, and processes as disparate as disturbance, dispersal, facilitation/competition and nutrient cycling, are related through ecological interaction networks; a ‘fractal’ is the ‘collective phenomenon’ of these networks.

Keywords: *biodynamic approach, forest integrity, fractal connectivity*

Introduction

Cyclic processes in the biosphere are self-organised and demonstrate sustainable development that inevitably involves change (Kazansky, 2010; Kimmins et al., 2007). The most important direct driver of change in forest biodiversity and ecosystems is habitat shifts and forest loss. Nearly half of the world’s original forest cover has been lost, yet the economic potential of a large part of the global forest area is under-realized because of a lack of sustainable forest management (FAO, 2014). Even if forest loss were to end today, it would take hundreds of years for species numbers to reach a new, lower, equilibrium in response to the habitat shifts that took place in recent centuries (Millennium Ecosystem Assessment, 2005). This means that since large areas are required to conserve viable populations and that since nature reserves eventually become isolated islands in the landscape, the long-term fate of many forest-dependent organisms will depend on activities and conditions in the unreserved portions of forests (Lindenmayer and Franklin, 2002; Whittaker et al., 2001; Kemp, 1992). For this reason, the present understanding of sustainable forest management must include values associated with integrity. A significant change, compatible with economic realities, requires the intrusion of biological considerations and conservationist philosophy into modern methods of exploitation (Stern and Roche, 1974). This calls for a biodynamic approach to forests and clearly addresses questions relating to scaling and self-organisation since the different levels of detail must be compatible to ensure the consistency of sustainability and diversity assessments.

Values associated with integrity, i.e., sustainability and diversity, are in essence about maintaining the combined biospherical-societal system: humans, with their social, cultural, economic, and environmental needs, are an integral part of ecosystems. It means that the capacity to sustainably use forests rests on our understanding and interpretation of pattern and process at several scales, the recognition of thresholds, and the ability to translate knowledge into appropriate management actions in a reflexive manner (Garmestani and Benson, 2013; Thompson et al., 2009). However, there is no single underpinning model that fully meets all the requirements for evaluating the sustainability of multi-functional forest management (Rennolls et al., 2007). So, the focus of attention shifts from the value components of sustainable development projects, to the domain of existence, in that we can map and model single, or even multiple relationships, but not a total set of evolving interactions and feedbacks (Fernandez et al., 2014; Jiggins and Röling, 2002; Waldrop, 1992). Here the reflexivity makes possible to connect any aspects of reality, setting up feedback loops between them (Soros, 2010). This, in turn, makes fractal organisation theory, inspired by systems theory, fractal geometry, quantum mechanics, information dynamics, sociobiology, epigenetics, evolutionary biology and game theory, the central subject herein (Raye, 2012).

Fractal organisation theory could illuminate evolving interactions and feedbacks from the multiple perspectives of different types, so it is a means to support the development of underpinning models which are consistent, and scale appropriately across the levels of self-organisation and conceptual frameworks. Forest integrity is about three aspects of self-organisation: resilience, health, and evolvability (Freedman, 2012; Kay and Regier, 2000). Evolvability, however, has not yet been studied because it was presumed at the outset: empirical experiences with quantitative genetics and selective breeding produced a consensus that ‘phenotypic variation was effectively like a gas which could flow into any selective bottle’ (Luo, 2014; Altenberg, 2014). Also, there is still no relevant notion of forest health, as there is for humans: a set of properties that have been selected through evolution because they maximize fitness (De Leo and Levin, 1997). Resilience is ‘the capacity to change in order to maintain the same identity’ (Folke et al., 2010). Accordingly, to support the development of a biodynamic approach to forests we review the concepts of self-organisation, criticality and resilience, and their relationship to forest integrity in the light of fractal organisation theory.

Scaling laws

Pattern integrity or self-similarity – the retention of distorted copies of itself across scales – is a typical property of fractals, a concept introduced by Benoît Mandelbrot (1924-2010) and one of the fundamental mathematical results of the 20th century (Satija, 2016; Raye, 2012; Rozenfeld et al., 2009). Fractals are often considered the ‘fingerprints of chaos’: the term ‘fractal’ is based on the Latin *fractus*, derived from *frangere* which signifies to break, to create irregular fragments (Mandelbrot, 1983). Also, a fractal is known as expanding symmetry or evolving symmetry (Kumar et al., 2017). Self-similarity is symmetry across scale. The manner, in which a fern leaf’s overall shape is replicated in each of its leaflets, and again in the subleaflets of each leaflet, is a familiar illustration of fractal relationship (Mosko, 2010). However, fractals are not extrapolated from a geometric logic based on units. Rather, we can think of

fractals as processes, possessing a self-replicating basis, which lead to a non-integer dimensionality (Fielder and King, 2014). Let's take, for example, the branching structures of resource distribution networks, such as the xylem that transport water through plants. According to West et al. (2009), 'the entire forest is, in a very real sense, a hierarchically branching resource supply network that can be described mathematically and behaves structurally and functionally like a scaled version of the branching network of the trees it contains': the analysis of the branching size distribution reveals an exponent which is essentially identical to the tree size distribution within a forest. So, a 'fractal' is what 'emerges' from these networks; it's the 'emergent property' of the network's memory. The analysis of fractality can provide a new strategy for studying cellular, organismal and community differentiation since fractal dimension is a good quantitative measure of the degree of morphological differentiation; it is also a useful measure for comparative studies across and among species, as they relate to cellular evolution (Smith and Behar, 1994). It should be noted, however, that the existence of changes in fractal dimension when shifting between scales implies that in place of true pattern integrity, we observe only partial self-similarity over a limited range of scales separated by transition zones. Fortunately, tests carried out using multifractals, which are objects that need a continuous spectrum of exponents to be described, may disclose the properties encoded in the data relating to the relationships on different scales; the basic graphic tools here are known as multifractal spectra or spectra of singularity (Drożdż and Oświecimka, 2015). On the other hand, real fractals are, in fact, multifractals: the measure is not the same in every subset, and each of them has a different fractal dimension and a different associated diverging exponent (Solé and Manrubia, 1995). Several good introductions to multifractal methods applied to ecology can be found in Scheuring and Riedi (1994) and Borda-de-Água et al. (2007) (Saravia, 2014). Multifractals have been applied to vegetal communities (Scheuring and Riedi, 1994), tropical rainforest (Manrubia and Solé, 1996), and to the characterisation of species-area relationships (Laurie and Perrier, 2011; Yakimov et al., 2008; Borda-de-Água et al., 2002). Borda-de-Água et al. (2007) used the so-called multifractal approach to show that models which assume symmetric neutral dynamics and use realistic dispersal kernels predict scaling patterns of diversity and distribution very similar to those observed by Hubbell and Foster (1983) in the Barro Colorado Island rainforest, in Panama. Solé and Manrubia (1995) constructed a simple cellular automata model in order to simulate the gap dynamics of the Barro Colorado Island rainforest as well as the observed macroscopic spatial regularities. The observed and simulated fractal behaviour was shown to be related to self-similar dynamics of biomass.

'From a wildlife perspective, each organism scales the environment differently, and thus there is no absolute size for a landscape' (Sun and Southworth, 2013). As scale changes, new patterns and processes may emerge and controlling factors may shift even for the same phenomena (Wu and Li, 2006). Fortunately, the fractal hierarchy is a method which can be used to unify different scaling phenomena and rules in complex systems (Seuront, 2009). 'The hierarchy always follows a pair of exponential laws and a power law' (Chen, 2012). Power laws describe empirical scaling relationships that are emergent quantitative features of biodiversity (Brown et al., 2002). A power law is obtained when one observes a straight line in a plot of 'the number of events' versus 'how often they occur'; in other words, the probability $f(x)$ of an event of magnitude x occurring is inversely proportional to x : $f(x) \sim x^{-\alpha}$ (Rhodes and Anderson, 1996). $f(x) \sim$

x^{-1} – a critical dependence – is often associated with ‘self-organised criticality’ which provides a general mechanism for the emergence of scale-free networks with the characteristic power-law distribution of links (Graham, 2014; Nottale, 2013; Laurienti et al., 2011; Messier and Puettmann, 2011; Turcotte, 1999; Bak et al., 1989). ‘Scale-free model’ incorporates two generic mechanisms thought to be common to many real-world networks: growth of the network by addition of nodes and links at each time step and preferential attachment of new nodes to certain highly connected hubs – the existing nodes with a high number of links. In other words, ‘A scale-free topology automatically emerges whenever new species (nodes) add preferentially to pre-existing ones with a probability proportional to the number of pairwise interactions (links) of the target species’ (Jordano et al., 2003). However, most ecological interaction networks examined so far have cut-off numbers of pairwise interactions per species giving rise to a gradient of variation from scale-free to broad-scale and to single-scale distributions; these distributions depart in most cases from the power-law beyond cut-off values. Constraints in the addition of links such as morphological mismatching or phenological uncoupling between mutualistic partners restrict the number of plant-animal interactions established, causing deviations from scale invariance, which is solely described by a power-law function, $f(x) = kx^\alpha$, where the power-law exponent, α , is a measure of scale-invariance, and k is a constant (Katz, 2016). In food webs, the distribution of links changes from (partial) power-law to exponential to uniform as the level of connectance increases (Dunne et al., 2002).

Self-organised phenomena

Nothing happens directly in this indirectly ordered universe (Schauberger, 1936). Unlike the action of seasons and natural disasters, long-term change in the composition of communities is brought about by the activities of living organisms which themselves inhabit the environment. Over a period of time, the environment is modified by these organisms so it becomes suitable for colonization by another species and less suitable for those already there (Rose, 2005). For example, after a stand-replacing disturbance, shade-intolerant species colonize and grow into a dominant canopy, but due to their shade-intolerance they are unable to regenerate under their own canopy, so the understory (composed of shade-tolerant species) gradually replaces the canopy (Kotar, 1997). Thus, all elements of any developing living system co-determine each other, whether it is the coevolution of biological species, a behavioural act or an immune response (Kazansky, 2015). Any living organism has relatively autonomous organisation of metabolic processes and, at the same time, all living creatures are fundamentally dependent on each other via trophic, behavioural or sexual relationships, and also indirectly, via the environment (Levchenko et al., 2012). A forest exists by virtue of all the fungi, trees, other plants, insects, birds and other animals, and they are fully what they are by virtue of dwelling in that forest; neither can ‘exist’, at least not fully, without the other.

‘Self-organisation is basically the spontaneous creation of a globally coherent pattern out of the local interactions between initially independent components’ (Heylighen, 2001). ‘In the optic of biological research, the common meaning of self-organisation is defined by the global emergence of a particular behaviour or feature that cannot be reduced to the properties of individual system’s components such as molecules, agents and cells’ (Camazine et al., 2003 as cited in Di Marzo Serugendo et al., 2011).

‘Physiological interactions among molecules, cells, tissues, organs do not simply sum each other up: they are “entangled”, “non-local”, “non-separable” . . . they are “superposed”’ (Longo and Montévil, 2011). Therefore, despite its intuitive simplicity as a concept, self-organisation has proven notoriously difficult to define and pin down formally or mathematically, and it is entirely possible that any precise definition might not include all the phenomena to which the label has been applied. One of the objectives of the present article was, therefore, to give prominence to the concepts of self-organised criticality and resilience because they are of relevance to forest integrity. As a result, forest integrity could be understood in terms of attractors as defined by conceptual inferences related to self-organised criticality and resilience (*Table 1*). The explanatory power of self-organised criticality stretches so far as to assume that a given scale-free phenomenon is caused by the system which organises its critical state by itself (Pruessner, 2012). This critical state acts as an attractor. The fractal patterns may be a fingerprint of a system close to a critical point (Manrubia and Solé, 1996). To substantiate such a viewpoint, Manrubia and Solé (1996) performed an extensive study of a real rainforest in Barro Colorado Island, Panama. They found the strong evidence of self-organised critical state in the power laws that the magnitudes of the system follow, both in space (fractality, correlation function, clearings and tree sizes distributions) and time (biomass fluctuations). Moreover, self-organised critical models of extinction have been used to explain power-law distributions of species’ life span and extinction events in statistical evidence from the fossil record (Solé et al., 1997; Solé and Bascompte, 1996; Sneppen et al., 1995; Bak and Sneppen, 1993).

Table 1. *System integrity in terms of attractors by conceptual inferences related to self-organised criticality and resilience*

Concept	Inference	Connection
Self-organisation	‘The basic mechanism underlying self-organisation is the variation which explores different regions in the system’s state space until it enters an attractor’ (Heylighen, 2001). ‘Standard examples of attractors are stable equilibrium and stable limit cycle’ (Fradkov and Chen, 2009). A limit cycle of infinite period is sometimes referred to as a chaotic state (Li and Yorke, 1975). An attractor – a region in state space that a system can enter but not leave – is a mathematical model of causal closure. ‘Closure usually results from the nonlinear, feedback nature of interactions’ (Heylighen, 2001). Therefore, it seems that reflexivity can act as an attractor when attempting to predict the outcome of a self-organising system at work (see Schiavello, 2013; Sandywell, 1996).	Reflexivity as an attractor
Criticality	‘Dynamical criticality, a central property for the functioning of a living organism, naturally emerges as a consequence of evolution that favours evolvability’ (Torres-Sosa et al., 2012). Also, it is a property of (classes of) dynamical systems that have a critical point as an attractor (Aschwanden, 2011; Bak and Creutz, 1994). Actually, many slowly driven open non-equilibrium systems self-organise to a critical point where everything can happen within well-defined statistical laws (Jensen, 1998; Bak, 1996; Bak et al., 1989). Moreover, as a system parameter changes through a critical value, a symmetry-broken attractor can be born (Lai, 1997). Lastly, when the symmetry is lost, it can be said that it is replaced by a collective mode.	Symmetry-broken attractor
Resilience	An ecosystem is resilient if it remains in the same domain of attraction and returns to the same state after a disturbance (Rietkerk and van de Koppel 2008). However, it may exist almost continuously in a transient state if there is frequent disturbance. So, it turns out that the final attractor toward which the system will converge (e.g., successional pattern, community type, etc.) usually depends on the initial conditions involving several attractors, leading to difficult issues related to the ability to predict which attractor a given trajectory will asymptote from (Freire et al., 2008; McDonald et al., 1985). Hypothetically, intransitivity, i.e., coexistence of attractors, is a peculiar characteristic of meta-communities without strict competitive hierarchies (Freire et al., 2008; Kerr et al., 2002).	Intransitivity of attraction

The basic assumption of resilience thinking is that systems are most resilient in their natural (evolved) states (Hopkins, 2009). Over the long run resilience is needed to maintain organismal fitness, however, the dynamics of organismal fitness remain poorly understood over long time scales (Wiser et al., 2013). Although researchers such as Kauffman (1993) have started exploring the structure of fitness landscapes for various formally defined systems by computer simulation, examples of individual adaptation via plasticity by temporal variation of fitness-related traits observed during the lifetime of forest organisms are very seldom documented at this time (see Lindner et al., 2008; Heylighen, 2001; Durzan, 1993). This leads to a reconsideration of the traditional approach to forests focused on long-term dynamics in favour of biodynamic approach. 'The commonly accepted fact is that the cell/organism (any living organisation, in fact) is an open nonequilibrium system, which exists and functions only because of the incessant flow of energy/matter passing through it' (Kurakin, 2011). For that reason, one of the most fascinating and mould-breaking findings has been the discovery of self-organised spiral/loop patterns, occurring commonly in nonliving and living nature (Luo and Zhan, 2008; Hill, 2006; Heylighen, 2001; Bascompte and Solé, 1998; Jean, 1994). Spirals exist in formations such as weather patterns because the interplay between physical forces and matter tend towards that shape, while they also exist in formations such as forests. Fractal hierarchy underlies these formations in all growth processes (Hill, 2006; Selvam, 1998). For example, a positive feedback loop that results in periodic organ formation has been recently uncovered behind the spiral patterns of leaves on a stem by Bhatia et al. (2016). According to Selvam (1998), such patterns are the clearest examples of self-organised criticality in the plant kingdom.

Resilience, or the stabilizing effect of feedback loops, is defined as the ability of an adaptive system to absorb impacts before a threshold between attractors is reached where the system changes into a different state altogether (Messier and Puettmann, 2011; Thompson et al., 2009; Heylighen, 2001). Since the reaching of an attractor is an automatic process it can be viewed as a general model of self-organisation. Most modelled systems with just one stable attractor (e.g., successional pattern, community type, etc.) tend to return to this attractor when perturbed in their dynamics. When the dynamical system has more than one coexisting attractor, it often turns out that the fractal boundaries of the basins of attraction are leading to difficult issues related to the ability to predict which attractor will a given trajectory asymptote to (McDonald et al., 1985). 'An observer might see one kind of behaviour over a very long time, yet a completely different kind of behaviour could be just as natural for the system' (Gleick, 2008). This implies intransitivity – a major factor stimulating emergence of chaotic dynamics (Klimenko, 2015; Lorenz, 1990; Crutchfield et al., 1986). Stone and Ezrati (1996) argued that chaos theory may be particularly useful in modelling vegetation change, where nonequilibrium dynamics (e.g., disturbance, natural mosaic cycling, and habitat fragmentation) often prevail (Kenkel and Walker, 1996). Nevertheless, emphasis on a broader understanding of possible system behaviours and the effects of human intervention has contributed to a significant shift toward resilience thinking, away from the mathematics of chaos.

Self-organisation of a self-sustainable ecological community is a highly-ordered non-random process based on information written in the genomes of participating species. 'The genetic program of species constitutes the informational basis for the compensatory environmental processes initiated by the biota when challenged by an environmental change' (Gorshkov et al., 2004). In a forest, species as different as fungi,

plants, animals and insects, and processes as disparate as disturbance, dispersal, facilitation/competition and nutrient cycling, are related through ecological interaction networks; a 'fractal' is the 'collective phenomenon' of these networks. Not coincidentally, loss of fractal dimension by a system implies loss of collectivity, i.e., capability of the interconnected components to interact in a common mode (Waliszewski et al., 1999). Moreover, if fractal space, in which a dynamic process takes place, becomes a classic, i.e., Euclidean, space with integer dimension, this means that the process has left its strange attractor, and tends towards, or already is in, the state with a lower number of possible directions of further evolution (Devaney, 1986). To sum up, in the light of fractal organisation theory, forest integrity refers to empirical scaling relationships that are emergent features of biodiversity (see Messier et al., 2015; Simard et al., 2013; Chen, 2012; Marks-Tarlow, 2012; Raye, 2012; Willerslev and Pedersen, 2010; Gorshkov et al., 2004; Brown et al., 2002; Turcotte and Rundle, 2002; Kirilyuk, 2002; Sandywell, 1996).

General suggestions

What is sustainability in the context of forest integrity? It is maintaining scaling relationships inherent to self-organisation (see Graham, 2014; Simard et al., 2013; Rozenfeld et al., 2009; Rickles et al., 2007; Sandywell, 1996). In the presence of intransitivity, the forces driving self-organisation can be analysed with game theory (the analysis of group interaction). However, intransitivity implies that every alternative is dominated by another alternative, so no one pure strategy can be argued to be any better than another (see Ficici and Pollack, 2003; Cooter, 2000). Therefore, sustainable forest management guided by the principles of self-organisation is to be based on a collective of strategies (see Graham, 2014; Cornett and White, 2013; Schütz, 2011; Willerslev and Pedersen, 2010; Li and Bowerman, 2010; Rennolls et al., 2007; Rickles et al., 2007; Millennium Ecosystem Assessment, 2005; Ficici and Pollack, 2003; Lindenmayer and Franklin, 2002; Lorenz, 1990). The two principles of the self-organisation are nature automation, like self-regeneration of a forest, self-differentiation of a stand, self-structuration of a community, etc., and concentration on essential, such as on a protecting key response traits and ecosystem legacies that are critical in the avoidance of a biodiversity threshold, i.e., an abrupt decline in species richness, with habitat loss (see Mackey et al., 2015; Estavillo et al., 2013; Simard et al., 2013; Holt and Miller, 2011; Thompson et al., 2009; Rickles et al., 2007; Schütz, 2006; Diaci, 2006; Kotar, 2006; Kerr et al., 2002; Cody, 1985). In this context, 'A critical management target is conservation of genetic legacies for the system memory and adaptive capacity they provide' (Simard et al., 2013). Unfortunately, 'the vital requirements of clarity, simplicity and practicality do not appear to have been seriously considered in the formulation of many of the genetic criteria and indicators developed to date for the management and monitoring of forest resources' (Boshier and Amaral, 2004; *Table 2*).

How can geneticists help forest biodiversity adapt to changing ecoclimates? First, there should be an effort to complete vulnerability assessments and action plans for forest tree species. For example, in the U.S. Pacific Northwest and Southern Appalachian regions the Forest Tree Genetic Risk Assessment System (ForGRAS) was used to rank forest tree species for a number of primary risk factors: population structure, rarity, regeneration capacity, dispersal ability, habitat affinity, genetic variation, pest and pathogen threats, and climate change pressure (Erickson et al.,

2012). Second, the conservation of biodiversity implies that the biotic verifiers, such as habitat shifts (*Table 2*), should necessarily be used by auditors and managers to derive an objective decision on the quality of the forest management under assessment. If wild organisms are extracted from their habitats and placed under artificial conditions never encountered in their natural environment, a decay of the genetic information will be manifested as an increase in genetic polymorphism of the populations and appearance of organisms with various defective properties not encountered in the wild type (Gorshkov and Makarieva, 1997; Gorshkov et al., 2004). Nevertheless, studies simulating the impact of forest exploitation, other silvicultural practices and forest fragmentation on genetic diversity are uncommon, and those that exist usually contain oversimplified representations of biological processes (Degen et al., 2004; Gorshkov et al., 2004).

An exploration of fractal connectivity behind key bioindicators and biomonitors in the avoidance of a biodiversity threshold can be suggested thus far. According to Holt and Miller (2011), bioindicators or biomonitors rely upon the complicated intricacies of ecosystems and use a representative or aggregated response to convey a dynamic picture of the condition of the environment. For instance, lichen diversity is commonly used as a general indicator of forest health and ‘ecological function’, as lichens are key primary producers with important linkages to nutrient cycling and forest food webs: high or low lichen diversity can result from certain types of air pollution, changes to forest management or stand structure, diversity of plant substrates available for colonization, favourability of forest climate, return interval of disturbances like fire, and so on (Jovan, 2008).

Table 2. Proposed indicators and verifiers of the maintenance of genetic diversity in sustainable forest management at interspecific, species and infraspecific levels. Sources: Déri et al. (2010), Rodriguez et al. (2009), Magura et al. (2006), Gorshkov et al. (2004), Boshier and Amaral (2004), Namkoong et al. (2002), Legendre and Legendre (1998)

Indicator	Biotic verifiers	Demographic verifiers	Genetic verifiers
Levels of variation	Species' site specificity Species' site fidelity Habitat affinity index	Census number of sexually mature individuals Census number of reproducing individuals Coefficient of phenotypic variation	Number of alleles Gene diversity Genetic variation
Directional change in allele or genotype frequencies	Habitat shifts	Phenotypic shifts Age/size class shifts Environmental shifts	Genotypic frequency shifts Marker frequency shifts Genetic mean shifts
Migration among populations	Forest removal Propagule removal	Physical isolation Mating isolation Seed dispersal Pollen dispersal	Gene flow
Reproductive processes/mating system	Biotic regulation Symbiotic regulation	Parental pool size Seed germination Pollinator abundance Sexuality	Outcrossing rate Correlated mating

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REFERENCES

- [1] Altenberg, L. (2014): Evolvability and robustness in artificial evolving systems: three perturbations. – *Genetic Programming and Evolvable Machines* 15: 275–280. doi: 10.1007/s10710-014-9223-3
- [2] Aschwanden, M. (2011): Self-organized criticality in astrophysics. The statistics of nonlinear processes in the universe. – Springer-Verlag, Berlin/Heidelberg. doi: 10.1007/978-3-642-15001-2
- [3] Bak, P. (1996): How nature works: the science of self-organized criticality. – Copernicus, Springer-Verlag, New York
- [4] Bak, P., Creutz, M. (1994): Fractals and self-organized criticality. – In: Bunde, A., Havlin, S. (eds) *Fractals in Science*. Springer-Verlag, Berlin/Heidelberg. Pp. 27–48. doi: 10.1007/978-3-662-11777-4_2
- [5] Bak, P., Chen, K., Creutz, M. (1989): Self-organized criticality in the 'Game of Life'. – *Nature* 342: 780–782. doi: 10.1038/342780a0
- [6] Bak, P., Sneppen, K. (1993): Punctuated equilibrium and criticality in a simple model of evolution. – *Physical Review Letters* 71: 4083–4086
- [7] Bascompte, J., Solé, R. V. (1998): Spatiotemporal patterns in nature. – *Trends in Ecology & Evolution* 13(5): 173–174. doi: 10.1016/S0169-5347(98)01325-1
- [8] Bhatia, N., Bozorg, B., Larsson, A., Ohno, C., Jönsson, H., Heisler, M. G. (2016): Auxin acts through MONOPTEROS to regulate plant cell polarity and pattern phyllotaxis. – *Current Biology* 26(23): 3202–3208. doi: 10.1016/j.cub.2016.09.044
- [9] Borda-de-Água, L., Hubbell, S. P., McAllister, M. (2002): Species-area curves, diversity indices, and species abundance distributions: a multifractal analysis. – *The American Naturalist* 159(2): 138–155
- [10] Borda-de-Água, L., Hubbell, S. P., He, F. (2007): Scaling biodiversity under neutrality. – In: Storch, D., Marquet, P., Brown J. (eds) *Scaling biodiversity*. Ecological reviews. Cambridge University Press, New York. Pp. 347–375. doi: 10.1017/CBO9780511814938.019
- [11] Boshier, D., Amaral, W. (2004): Threats to forest ecosystems and challenges for the conservation and sustainable use of forest genetic resources. – In: Vinceti, B., Amaral, W., Meilleur, B. (eds) *Challenges in managing forest genetic resources for livelihoods: examples from Argentina and Brazil*. International Plant Genetic Resources Institute, Rome, Italy. Pp. 7–28
- [12] Brown, J. H., Gupta, V. K., Li, B. L., Milne, B. T., Restrepo, C., West, G. B. (2002): The fractal nature of nature: power laws, ecological complexity and biodiversity. – *Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences* 357(1421): 619–626
- [13] Camazine, S., Deneubourg, J. L., Franks, N. R., Sneyd, J., Théraulaz, G., Bonabeau, E. (2003): *Self-organization in biological systems*, 2nd edn. – Princeton University Press, Princeton, NJ
- [14] Chen, Y. G. (2012): Zipf's law, 1/f noise, and fractal hierarchy. – *Chaos, Solitons & Fractals* 45: 63–73. doi: 10.1016/j.chaos.2011.10.001
- [15] Cody, M. L. (1985): *Habitat selection in birds*. – Academic Press, Orlando, FL
- [16] Cooter, R. (2000): *The strategic constitution*. – Princeton University Press, Princeton, NJ

- [17] Cornett, M., White, M. (2013): Forest restoration in a changing world: complexity and adaptation examples from the Great Lakes region of North America. – In: Messier, C., Puettmann, K., Coates, K. D. (eds) *Managing forests as complex adaptive systems: building resilience to the challenge of global change*. The Earthscan forest library. Routledge, New York. Pp. 113–132
- [18] Crutchfield, J. P., Farmer, J. D., Packard, N. H., Shaw, R. S. (1986): Chaos. – *Scientific American* 254: 46–57
- [19] De Leo, G. A., Levin, S. (1997): The multifaceted aspects of ecosystem integrity. – *Conservation Ecology* 1: 3. <http://www.consecol.org/vol1/iss1/art3/>. Accessed 12 June 2015
- [20] Degen, B., Jarvis, A., Vinceti, B. (2004): Modelling the biological processes: from genes to ecosystems. – In: Vinceti, B., Amaral, W., & Meilleur, B. (eds) *Challenges in managing forest genetic resources for livelihoods: examples from Argentina and Brazil*. International Plant Genetic Resources Institute, Rome, Italy. Pp. 71–90
- [21] Déri, E., Magura, T., Horváth, R., Kisfal, M., Ruff, G., Lengyel, S., Tóthmérész, B. (2010): Measuring the short-term success of grassland restoration: the use of habitat affinity indices in ecological restoration. – *Restoration Ecology* 19(4): 520–528. doi: 10.1111/j.1526-100X.2009.00631.x
- [22] Devaney, R. L. (1986): *An introduction to chaotic dynamical systems*. – Benjamin/Cummings, Menlo Park, CA. Pp. 176–202
- [23] Di Marzo Serugendo, G., Gleizes, M.-P., Karageorgos, A. (2011): Self-organising systems. – In: Di Marzo Serugendo, G., Gleizes, M.-P., Karageorgos, A. (eds) *Self-organising software: from natural to artificial adaptation*. Springer-Verlag, Berlin/Heidelberg. Pp. 7–32
- [24] Diaci, J. (2006): Nature-based silviculture in Slovenia: origins, development and future trends. – *Studia Forestalia Slovenica* 126: 119–131
- [25] Drożdż, S., Oświecimka, P. (2015): Detecting and interpreting distortions in hierarchical organization of complex time series. – *Physical Review E*. doi: 10.1103/PhysRevE.91.030902
- [26] Dunne, J. A., Williams, R. J., Martinez, N. D. (2002): Food-web structure and network theory: the role of connectance and size. – *Proceedings of the National Academy of Sciences of the United States of America* 99(20): 12917–12922
- [27] Durzan, D. J. (1993): Molecular bases for adaptation of coniferous trees to cold climates. – In: Alden, J. N., Ødum, S., & Mastrantonio, J. L. (eds) *Forest development in cold climates*. NATO ASI series. Life sciences, 244. Plenum Press, New York. Pp. 15–42
- [28] Erickson, V., Aubry, C., Berrang, P., Blush, T., Bower, A., Crane, B., DeSpain, T., Gwaze, D., Hamlin, J., Horning, M., Johnson, R., Mahalovich, M., Maldonado, M., Snieszko, R., St Clair, B. (2012): Genetic resource management and climate change: genetic options for adapting national forests to climate change. – USDA Forest Service, Forest Management, Washington, DC
- [29] Estavillo, C., Pardini, R., Da Rocha, P. L. B. (2013): Forest loss and the biodiversity threshold: an evaluation considering species habitat requirements and the use of matrix habitats. – *PLoS ONE* 8(12): e82369. doi: 10.1371/journal.pone.0082369
- [30] FAO. (2014): Forestry. <http://www.fao.org/forestry/en/>. Accessed 3 February 2014
- [31] Fernandez, N., Maldonado, C., Gershenson, C. (2014): Information measures of complexity, emergence, self-organization, homeostasis, and autopoiesis. – In: Prokopenko, M. (ed.) *Guided self-organization: inception*. ECC series, 9. Springer, Berlin Heidelberg. Pp. 19–51. doi: 10.1007/978-3-642-53734-9_2
- [32] Ficici, S. G., Pollack, J. B. (2003): A game-theoretic memory mechanism for coevolution. In: Cantú-Paz, E. et al. (eds.). *Proceedings of the Genetic and Evolutionary Computation Conference*, Chicago, IL, USA, July 12–16, 2003. Lecture notes in computer science, 2723. Springer-Verlag, Berlin/Heidelberg. Pp. 286–297

- [33] Fielder, C., King, C. (2014): The sensitivity of chaos. <http://www.dhushara.com/paradoxhtm/chaos.htm>. Accessed 9 March 2015
- [34] Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., Rockström, J. (2010): Resilience thinking: integrating resilience, adaptability and transformability. – *Ecology and Society* 15(4): 20. <http://www.ecologyandsociety.org/vol15/iss4/art20/>. Accessed 12 October 2016
- [35] Fradkov, A. L., Chen, G. (2009): Control of chaos and bifurcations. – In: Unbehauen, H. D. (ed.) *Control systems, robotics and automation. Encyclopedia of life support systems (EOLSS), Vol. XIII*. Eolss Publishers, Oxford. Pp. 230–259. <http://www.eolss.net>. Accessed 12 February 2017
- [36] Freedman, B. (2012): Ecological integrity – indicators of ecological integrity – species, ecosystems, populations, and stress. <http://science.jrank.org/pages/2251/Ecological-Integrity-Indicators-ecological-integrity.html>. Accessed 13 April 2016
- [37] Freire, J. G., Bonatto, C., DaCamara, C. C., Gallas, J. A. C. (2008): Multistability, phase diagrams, and intransitivity in the Lorenz-84 low-order atmospheric circulation model. – *Chaos* 18: 033121. doi: 10.1063/1.2953589
- [38] Garmestani, A. S., Benson, M. H. (2013): A framework for resilience-based governance of social-ecological systems. – *Ecology and Society* 18(1): 9. doi: 10.5751/ES-05180-180109
- [39] Gleick, J. (2008): *Chaos: making a new science*, 20th anniversary edn. – Penguin Books, New York
- [40] Gorshkov, V. G., Makarieva, A. M. (1997): Dependence of heterozygosity on body weight in mammals. – *Doklady Biological Sciences* 355: 384–386.
- [41] Gorshkov, V. G., Makarieva, A. M., Gorshkov, V. V. (2004): Revising the fundamentals of ecological knowledge: the biota-environment interaction. – *Ecological Complexity* 1: 17–36. doi:10.1016/j.ecocom.2003.09.002
- [42] Graham, B. (2014): *Nature's patterns: exploring her tangled web*, 2nd edn. – FreshVista
- [43] Heylighen, F. (2001): The science of self-organization and adaptivity. – In: Kiel, L. D. (ed.) *Knowledge management, organizational intelligence and learning, and complexity. Encyclopedia of life support systems (EOLSS), Vol. III*. Eolss Publishers, Oxford. Pp. 849–874. <http://www.eolss.net>. Accessed 28 November 2016
- [44] Hill, C. (2006): *Electro-fractal universe*. <http://www.fractaluniverse.eclipse.co.uk/ElectroFractalUniverseWebVersion.pdf>. Accessed 30 January 2017
- [45] Holt, E. A., Miller, S. W. (2011): Bioindicators: using organisms to measure environmental impacts. – *Nature Education Knowledge* 2(2): 8. <http://www.nature.com/scitable/knowledge/library/bioindicators-using-organisms-to-measure-environmental-impacts-16821310>. Accessed 13 October 2016
- [46] Hopkins, D. (2009): Resilience and regime change in ecosystems: bifurcation and perturbation analysis. https://math.dartmouth.edu/archive/m53f09/public_html/. Accessed 22 March 2017
- [47] Hubbell, S. P., Foster, R. B. (1983): Diversity of canopy trees in a neotropical forest and implications for the conservation of tropical trees. – In: Sutton, S. J., Whitmore, T. C., Chadwick, A. C. (eds) *Tropical rain forest: ecology and management*. Blackwell, Oxford. Pp. 25–41
- [48] Jean, R. V. (1994): *Phyllotaxis: a systemic study in plant morphogenesis*. – Cambridge University Press, NY, USA
- [49] Jensen, H. J. (1998): *Self-organised criticality*. – Cambridge University Press, Cambridge, UK
- [50] Jiggins, J., Röling, N. (2002): Adaptive management: potential and limitations for ecological governance of forests in a context of normative pluriformity. – In: Oglethorpe, J. A. E. (ed.) *Adaptive management: from theory to practice*. SUI technical series, 3.

- International Union for the Conservation of Nature and Natural Resources, Gland, Switzerland. Pp. 93–103
- [51] Jordano, P., Bascompte, J., Olesen, J. M. (2003): Invariant properties in coevolutionary networks of plant-animal interactions. – *Ecology Letters* 6: 69–81. doi: 10.1046/j.1461-0248.2003.00403.x
 - [52] Jovan, S. (2008): Lichen bioindication of biodiversity, air quality, and climate: baseline results from monitoring in Washington, Oregon, and California. Gen. Tech. Rep. PNW-GTR-737. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR
 - [53] Katz, J. S. (2016): What is a complex innovation system? – *PLoS ONE* 11(6): e0156150. doi: 10.1371/journal.pone.0156150
 - [54] Kauffman, S. A. (1993): The origins of order: self-organization and selection in evolution. – Oxford University Press, New York
 - [55] Kay, J. J., Regier, H. (2000): Uncertainty, complexity, and ecological integrity: insights from an ecosystem approach. – In: Crabbé, P., Holland, A., Ryszkowski, L., Westra, L. (eds) *Implementing ecological integrity: restoring regional and global environmental and human health*. NATO science series. Environmental security. Kluwer, The Netherlands. Pp. 121–156
 - [56] Kazansky, A. B. (2010): Bootstrapping of life through holonomy and self-modification. Computing anticipatory systems. – In: Dubois, D. M. (ed.) *Proceedings of the 9th International Conference on Computing Anticipatory Systems*. AIP conference proceedings, 1303. American Institute of Physics, Melville, New York. Pp. 297–306
 - [57] Kazansky, A. B. (2015): Agential anticipation in the central nervous system: anticipation. – In: Nadin, M. (ed.) *Learning from the past, the Russian/Soviet contributions to the science of anticipation*. Cognitive systems monographs, 25. Springer International Publishing, Switzerland. Pp. 101–112
 - [58] Kemp, R. H. (1992): ITTO and the conservation of biological diversity. – In: Blockhus, J. M., Dillenbeck, M., Sayer, J. A., Wegge, P. (eds) *Conserving biological diversity in managed tropical forests*. International Union for Conservation of Nature and Natural Resources (IUCN), Cambridge, UK
 - [59] Kenkel, N. C., Walker, D. J. (1996): Fractals in the biological sciences. – *Coenoses* 11: 77–100
 - [60] Kerr, B., Riley, M. A., Feldman, M. W., Bohannan, B. J. M. (2002): Local dispersal promotes biodiversity in a real-life game of rock–paper–scissors. – *Nature* 418: 171–174. doi: 10.1038/nature00823
 - [61] Kimmins, J. P., Rempel, R. S., Welham, C. V. J., Seely, B., Van Rees, K. C. J. (2007): Biophysical sustainability, process-based monitoring and forest ecosystem management decision support systems. – *The Forestry Chronicle* 83(4): 502–514
 - [62] Kirilyuk, A. P. (2002): The universal dynamic complexity as extended dynamic fractality: causally complete understanding of living systems emergence and operation. – In: Losa, G. A., Merlini, D., Nonnenmacher, T. F., Weibel, E. R. (eds) *Fractals in biology and medicine*, Vol. III. Mathematics and biosciences in interaction. Birkhäuser, Basel, Switzerland. Pp. 271–284. doi: 10.1007/978-3-0348-8119-7_27
 - [63] Klimenko, A. Y. (2015): Intransitivity in theory and in the real world. – *Entropy* 17: 4364–4412. doi: 10.3390/e17064364
 - [64] Kotar, J. (1997): Forest dynamics. Approaches to ecologically based forest management on private lands. U.S. Department of Agriculture, Forest Service, Northeast Area State and Private Forestry, University of Minnesota Extension Service. <http://www.na.fs.fed.us/pubs/detail.cfm?id=2953/>. Accessed 24 May 2016
 - [65] Kotar, M. (2006): Sustainable and multipurpose forest management with production of high quality timber. – *Studia Forestalia Slovenica* 126: 153–167
 - [66] Kumar, D. K., Arjunan, S. P., Aliahmad, B. (2017): Fractals: applications in biological signalling and image processing. – CRC Press, Boca Raton, FL

- [67] Kurakin, A. (2011): The self-organizing fractal theory as a universal discovery method: the phenomenon of life. – *Theoretical Biology and Medical Modelling* 8: 4. doi: 10.1186/1742-4682-8-4
- [68] Lai, Y.-C. (1997): Scaling laws for symmetry breaking by blowout bifurcation in chaotic systems. – *Physical Review E* 56: 1407. doi: 10.1103/PhysRevE.56.1407
- [69] Laurie, H., Perrier, E. (2011): Beyond species area curves: application of a scale-free measure for spatial variability of species richness. – *Oikos* 120(7): 966–978
- [70] Laurienti, P. J., Joyce, K. E., Telesford, Q. K., Burdette, J. H., Hayasaka, S. (2011): Universal fractal scaling of self-organized networks. – *Physica A* 390(20): 3608–3613. doi: 10.1016/j.physa.2011.05.011
- [71] Legendre, P., Legendre, L. (1998): *Numerical ecology*, 2nd English edn. – Elsevier, Amsterdam, The Netherlands
- [72] Levchenko, V. F., Kazansky, A. B., Sabirov, M. A., Semenova, E. M. (2012): Early biosphere: origin and evolution. – In: Isshwaran, N. (ed.) *The biosphere*. InTech. Pp 3–32
- [73] Li, T.-Y., Yorke, J. A. (1975): Period three implies chaos. – *The American Mathematical Monthly* 82(10): 988–992
- [74] Li, R., Bowerman, B. (2010): Symmetry breaking in biology. – *Cold Spring Harbor Perspectives in Biology* 2(3): a003475. doi: 10.1101/cshperspect.a003475
- [75] Lindenmayer, D. B., Franklin, J. F. (2002): *Conserving forest biodiversity: a comprehensive multiscaled approach*. – Island Press, Covelo, CA
- [76] Lindner, M., Garcia-Gonzalo, J., Kolström, M., Green, T., Reguera, R., Maroschek, M., Seidl, R., Lexer, M. J., Netherer, S., Schopf, A., Kremer, A., Delzon, S., Barbati, A., Marchetti, M., Corona, P. (2008): Impacts of climate change on European forests and options for adaptation. Report to the European Commission Directorate-General for Agriculture and Rural Development (AGRI-2007-G4-06). European Forest Institute (EFI), Universität für Bodenkultur Wien (BOKU), UMR Biodiversité Gènes et Communautés (INRA), Italian Academy of Forest Sciences (IAFS). http://ec.europa.eu/agriculture/analysis/external/euro_forests/index_en.htm. Accessed 8 February 2016
- [77] Longo, G., Montévil, M. (2011): From physics to biology by extending criticality and symmetry breakings. Invited paper, special issue: Systems Biology and Cancer. *Progress in Biophysics and Molecular Biology* 106(2): 340–347. doi: 10.1016/j.pbiomolbio.2011.03.005
- [78] Lorenz, E. N. (1990): Can chaos and intransitivity lead to interannual variability? – *Tellus* 42A: 378–389
- [79] Luo, J. (2014): Loops and autonomy promote evolvability of ecosystem networks. – *Scientific Reports* 4: 6440. doi: 10.1038/srep06440
- [80] Luo, J., Zhan, M. (2008): Electric-field-induced wave groupings of spiral waves with oscillatory dispersion relation. – *Physical Review E* 78: 016214. doi: 10.1103/PhysRevE.78.016214
- [81] Mackey, B., DellaSala, D. A., Kormos, C., Lindenmayer, D., Kumpel, N., Zimmerman, B., Hugh, S., Young, V., Foley, S., Arsenis, K., Watson, J. E. M. (2015): Policy options for the world's primary forests in multilateral environmental agreements. – *Conservation Letters* 8: 139–147. doi: 10.1111/conl.12120
- [82] Magura, T., Tóthmérész, B., Elek, Z. (2006): Changes in carabid beetle assemblages as Norway spruce plantations age. – *Community Ecology* 7: 1–12
- [83] Mandelbrot, B. B. (1983): *The fractal geometry of nature*, 2nd edn. – Macmillan, London
- [84] Manrubia, S. C., Solé, R. V. (1996): Self-organized criticality in rainforest dynamics. – *Chaos, Solitons & Fractals* 7(4): 523–541
- [85] Marks-Tarlow, T. (2012): Fractal geometry as a bridge between realms. – In: Orsucci, F., Sala, N. (eds) *Complexity science, living systems, and reflexing interfaces: new models and perspectives*. Nova Science, Hauppauge, New York. P. 33

- [86] McDonald, S. W., Grebogi, C., Ott, E., Yorke, J. A. (1985): Fractal basin boundaries. – *Physica D* 17(2): 125–153. doi: 10.1016/0167-2789(85)90001-6
- [87] Messier, C., Puettmann, K. J. (2011): Forests as complex adaptive systems: implications for forest management and modelling. – *L'Italia Forestale e Montana* 66(3): 249–258. doi: 10.4129/ifm.2011.3.11
- [88] Messier, C., Puettmann, K. J., Chazdon, R., Andersson, K. P., Angers, V. A., Brotons, L., Filotas, E., Tittler, R., Parrott, L., Levin, S. A. (2015): From management to stewardship: viewing forests as complex adaptive systems in an uncertain world. – *Conservation Letters* 8(5): 368–377. doi: 10.1111/conl.12156
- [89] Millennium Ecosystem Assessment. (2005): Ecosystems and human well-being: biodiversity synthesis. – World Resources Institute, Washington, DC
- [90] Mosko, M. (2010): Deep wholes: fractal holography in Trobriand agency and culture. – In: Otto, T., Bubandt, N. (eds) *Experiments in holism: theory and practice in contemporary anthropology*. Wiley-Blackwell, Oxford. Pp. 150–173
- [91] Namkoong, G., Boyle, T., El-Kassaby, Y. A., Palmberg-Lerche, C., Eriksson, G., Gregorius, H.-R., Joly, H., Kremer, A., Savolainen, O., Wickneswari, R., Young, A., Zeh-Nlo, M., Prabhu, R. (2002): Criteria and indicators for sustainable forest management: assessment and monitoring of genetic variation. Forest Genetic Resources Working Paper FGR/37E, Forest Resources Development Service, Forest Resources Division, Forestry Department, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy
- [92] Nottale, L. (2013): Lecture 19. Scale relativity. – In: Dubrulle, B., Graner, F., Sornette, D. (eds) *Scale invariance and beyond*. Les Houches Workshop, March 10–14, 1997. EDP sciences. Springer-Verlag, Berlin/Heidelberg. Pp. 249–261. doi: 10.1007/978-3-662-09799-1
- [93] Pruessner, G. (2012): Self-organised criticality: theory, models and characterisation. – Cambridge University Press, Cambridge
- [94] Raye, J. (2012): Fractal organization theory. – In: Wilby, J. (ed.) *Proceedings of the 56th Annual Meeting of the ISSS. International Society for the Systems Sciences*, San Jose, CA. <http://journals.iss.org/index.php/proceedings56th/article/viewFile/1796/663/>. Accessed 3 February 2015
- [95] Rennolls, K., Tomé, M., McRoberts, R. E., Vanclay, J. K., LeMay, V., Guan, B. T., Gertner, G. Z. (2007): Potential contributions of statistics and modelling to sustainable forest management: review and synthesis. – In: Reynolds, K. M., Thomson, A. J., Köhl, M., Shannon, M. A., Ray, D., Rennolls, K. (eds) *Sustainable forestry: from monitoring and modelling to knowledge management & policy science*. CABI, Wallingford, UK. Pp 314–341
- [96] Rhodes, C. J., Anderson, R. M. (1996): Power laws governing epidemics in isolated populations. – *Nature* 381: 600–602
- [97] Rickles, D., Hawe, P., Shiell, A. (2007): A simple guide to chaos and complexity. – *Journal of Epidemiology and Community Health* 61: 933–937. doi: 10.1136/jech.2006.054254
- [98] Rietkerk, M., van de Koppel, J. (2008): Regular pattern formation in real ecosystems. – *Trends in Ecology & Evolution* 23(3): 169–75. doi: 10.1016/j.tree.2007.10.013
- [99] Rodriguez, R. J., Freeman, D. C., McArthur, E. D., Kim, Y. O., Redman, R. S. (2009): Symbiotic regulation of plant growth, development and reproduction. – *Communicative & Integrative Biology* 2(2): 141–143
- [100] Rose, B. (2005): Tree ecology. <http://www.monkeydo.net/sites/default/files/Tree%20ecology.pdf>. Accessed 2 September 2015
- [101] Rozenfeld, H. D., Gallos, L. K., Song, C., Makse, H. A. (2009): Fractal and transfractal scale-free networks. – In: Meyers, R. A. (ed.) *Encyclopedia of complexity and systems science*, 00611. Springer, New York. Pp. 3924–3943. doi: 10.1007/978-0-387-30440-3_231

- [102] Sandywell, B. (1996): Reflexivity and the crisis of Western reason. Logological investigations, 1. – Routledge, London
- [103] Saravia, L. A. (2014): mfSBA: Multifractal analysis of spatial patterns in ecological communities. – F1000Research 3: 14. doi: 10.12688/f1000research.3-14.v2
- [104] Satija, I. I. (2016): Butterfly in the quantum world: the story of the most fascinating quantum fractal. – IOP Publishing, Bristol, UK
- [105] Schauburger, V. (1936): The dying forest. – TAU Magazin 151: 20–30
- [106] Scheuring, I., Riedi, R. H. (1994): Application of multifractals to the analysis of vegetation pattern. – Journal of Vegetation Science 5(4): 489–496
- [107] Schiavello, A. (2013): The third theory of legal objectivity. – In: Araszkievicz, M., Šavelka, J. (eds) Coherence: insights from philosophy, jurisprudence and artificial intelligence. Law and philosophy library, 107. Springer Science & Business Media, Dordrecht. Pp. 137–139
- [108] Schütz, J.-P. (2006): Opportunities and strategies of biorationalisation of forest tending within nature-based management. – Studia Forestalia Slovenica 126: 39–46
- [109] Schütz, J.-P. (2011): Development of close to nature forestry and the role of ProSilva Europe. – Zbornik Gozdarstva in Lesarstva: 94, 39–42
- [110] Selvam, A. M. (1998): Quasicrystalline pattern formation in fluid substrates and phyllotaxis. – In: Barabe, D., Jean, R. V. (eds) Symmetry in Plants. World Scientific series, 4. Mathematical biology and medicine. World Scientific, Singapore. Pp. 795–805
- [111] Seuront, L. (2009): Fractals and multifractals in ecology and aquatic science. – CRC Press, New York
- [112] Simard, S. W., Martin, K., Vyse, A., Larson, B. (2013): Meta-networks of fungi, fauna and flora as agents of complex adaptive systems. – In: Messier, C., Puettmann, K. J., Coates, K. D. (eds) Managing world forests as complex adaptive systems. Routledge, London. Pp. 133–164
- [113] Smith, T. G. Jr., Behar, T. N. (1994): Comparative fractal analysis of cultured glia derived from optic nerve and brain demonstrate different rates of morphological differentiation. – Brain Research 634: 181–190
- [114] Sneppen, K., Bak, P., Flyvbjerg, H., Jensen, M. H. (1995): Evolution as a self-organized critical phenomenon. – Proceedings of the National Academy of Sciences of the United States of America 92: 5209–5213
- [115] Solé, R. V., Bascompte, J. (1996): Are critical phenomena relevant to large-scale evolution? – Proceedings of the Royal Society of London B263: 161–168
- [116] Solé, R. V., Manrubia, S. C. (1995): Are rainforests self-organized in a critical state? – Journal of Theoretical Biology 173: 31–40
- [117] Solé, R. V., Manrubia, S. C., Benton, M., Bak, P. (1997): Self-similarity of extinction statistics in the fossil record. – Nature 388: 764–767
- [118] Soros, G. (2010): The Soros lectures: at the Central European University. – PublicAffairs, New York
- [119] Stern, K., Roche, L. (1974): Genetics of forest ecosystems. Ecological Studies series, 6. – Springer-Verlag, Berlin Heidelberg New York. doi: 10.1007/978-3-642-65517-3
- [120] Stone, L., Ezrati, S. (1996): Chaos, cycles and spatiotemporal dynamics in plant ecology. – Journal of Ecology 84: 279–291
- [121] Sun, J., Southworth, J. (2013): Remote sensing-based fractal analysis and scale dependence associated with forest fragmentation in an Amazon tri-national frontier. – Remote Sensing 5: 454–472
- [122] Thompson, I., Mackey, B., McNulty, S., Mosseler, A. (2009): Forest resilience, biodiversity, and climate change. A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems. Technical series, 43. Secretariat of the Convention on Biological Diversity, Montreal. Pp. 1–67

- [123] Torres-Sosa, C., Huang, S., Aldana, M. (2012): Criticality Is an emergent property of genetic networks that exhibit evolvability. – *PLoS Computational Biology* 8(9): e1002669. doi: 10.1371/journal.pcbi.1002669
- [124] Turcotte, D. L. (1999): Self-organized criticality. – *Reports on Progress in Physics* 62: 1377–1429
- [125] Turcotte, D. L., Rundle, J. B. (2002): Self-organized complexity in the physical, biological, and social sciences. – *Proceedings of the National Academy of Sciences of the United States of America* 99: 2463–2465
- [126] Waldrop, M. M. (1992): *Complexity: the emerging science at the edge of complexity and chaos*. – Simon & Schuster, New York
- [127] Waliszewski, P., Molski, M., Konarski, J. (1999): Self-similarity, collectivity, and evolution of fractal dynamics during retinoid-induced differentiation of cancer cell population. – *Fractals* 7: 139–149
- [128] West, G. B., Enquist, B. J., Brown, J. H. (2009): A general quantitative theory of forest structure and dynamics. – *Proceedings of the National Academy of Sciences of the United States of America* 106: 7040–7045
- [129] Whittaker, R. J., Willis, K. J., Field, R. (2001): Scale and species richness: towards a general, hierarchical theory of species diversity. – *Journal of Biogeography* 28: 453–470. doi: 10.1046/j.1365-2699.2001.00563.x
- [130] Willerslev, R., Pedersen, M. A. (2010): Proportional holism: joking the cosmos into the right shape in North Asia. – In: Otto, T., Bubandt, N. (eds) *Experiments in holism: theory and practice in contemporary anthropology*. Wiley-Blackwell, Oxford. Pp. 262–278
- [131] Wiser, M. J., Ribbeck, N., Lenski, R. E. (2013): Long-term dynamics of adaptation in asexual populations. – *Science*, 342(6164), 1364–1367. doi: 10.1126/science.1243357
- [132] Wu, J., Li, H. (2006): Concepts of scale and scaling. – In: Wu, J., Jones, B., Li, H., Loucks, O. (eds) *Scaling and uncertainty analysis in ecology: methods and applications*. Springer, Dordrecht. Pp. 3–16
- [133] Yakimov, B. N., Bossuyt, B., Iudin, D. I., Gelashviliy, D. B. (2008): Multifractal diversity-area relationship at small scales in dune slack plant communities. – *Oikos* 117(1): 33–39