

2012, 2012, L, 14869 p. 2500 illus. in color.

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REFERENCE

Print (Book)

- ▶ 6.000,00 € | £5,400.00 | \$8,100.00
- ▶ *6.420,00 € (D) | 6.600,00 € (A) | CHF 8'602.00

eReference

- ▶ 6.000,00 € | £5,400.00 | \$8,100.00
- ▶ *7.140,00 € (D) | 7.200,00 € (A) | CHF 9'038.50

Print + eReference

- ▶ 7.500,00 € | £6,750.00 | \$10,150.00
- ▶ *8.025,00 € (D) | 8.250,00 € (A) | CHF 10'752.00

R.A. Meyers, RAMTECH Ltd., Larkspur, CA, USA (Ed.)

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Metadata of the chapter that will be visualized online

Chapter Title	Landscape Ecology	
Copyright Year	2011	
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Abstract

Landscapes are spatially heterogeneous areas characterized by diverse patches that differ in size, shape, contents, and history. When spatial heterogeneity is considered, scale matters and hierarchy emerges. Landscape ecology is the science and art of studying and improving the relationship between spatial pattern and ecological processes on a multitude of scales and organizational levels. In a broad sense, landscape ecology represents both a field of study and a scientific paradigm. As a highly interdisciplinary and transdisciplinary enterprise, landscape ecology integrates biophysical and analytical approaches with humanistic and holistic perspectives across natural and social sciences. Landscape ecology was initially developed in Europe. With theoretical developments in spatial ecology and technological advances in remote sensing and geospatial information processing, landscape ecology became an internationally recognized field of study in the 1980s. The most salient characteristics of landscape ecology are its emphasis on the pattern-process relationship and its focus on broad-scale ecological and environmental issues. Key research topics in landscape ecology include ecological flows in landscape mosaics, land use and land cover change, scaling, relating landscape pattern analysis with ecological processes, and landscape conservation and sustainability.

L

2 **Landscape Ecology**

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6 **Article Outline**

- 7 Glossary
- 8 Definition of the Subject
- 9 Introduction
- 10 What is Landscape Ecology?
- 11 Key Research Topics in Landscape Ecology
- 12 Future Directions
- 13 Bibliography

14 **Glossary**

15 **Landscape** A geographic area in which at least one
16 variable of interest is spatially heterogeneous. The
17 boundary of a landscape may be delineated based
18 on geographic, ecological, or administrative units
19 (e.g., watersheds, ecosystem mosaics, or metropol-
20 itan regions) which are relevant to the research
21 questions and objectives.

22 **Landscape connectivity** The degree of a landscape to
23 facilitate or impede the flows of organisms, energy,
24 material, and information among landscape ele-
25 ments. This is sometimes referred to as landscape
26 functional connectivity, which is a function of both
27 landscape structural connectivity and the move-
28 ment characteristics of the species or process
29 under consideration. Landscape structural connec-
30 tivity is simply a measure of how spatially
31 connected the elements in a landscape are, without
32 reference to any particular ecological process.

33 **Landscape ecology** The science of studying and
34 improving the relationship between spatial pattern
35 and ecological processes on multiple scales.

Landscape ecology studies the structure, function, 36
and dynamics of landscapes of different kinds, 37
including natural, seminatural, agricultural, and 38
urban landscapes. 39

Landscape fragmentation The breaking-up of land- 40
scape into smaller patches by anthropogenic 41
activities, or the human introduction of barriers 42
that impede flows of organisms, energy, material, 43
and information across a landscape. Habitat 44
fragmentation is a similar term to landscape 45
fragmentation, but has a more explicit focus on 46
changes in habitat of organisms of interest. 47

Landscape pattern The composition (diversity and 48
relative abundances) and configuration (shape, 49
size, and spatial arrangement) of landscape ele- 50
ments, including both spatial patchiness and 51
gradients. 52

Landscape function The horizontal and vertical flows 53
of organisms, energy, material, and information in 54
a landscape. 55

Landscape structure The composition and spatial 56
arrangement of landscape elements – including 57
patches, corridors, and the matrix. 58

Landscape dynamics Temporal changes in the struc- 59
ture and function of a landscape, driven by natural 60
and anthropogenic processes. 61

Landscape sustainability The ability of a landscape to 62
maintain its basic environmental, economic, and 63
social functions under ever-changing conditions 64
driven by human activities and climate change. 65
Landscape sustainability emphasizes scale-multi- 66
plicity, self-organization, and spatial optimization 67
of landscape pattern so as to achieve a high level of 68
resilience and metastability. 69

Metapopulation The total population system that is 70
composed of multiple local populations geograph- 71
ically separated but functionally connected through 72
dispersal. 73

Patch dynamics A perspective that ecological 74
systems are mosaics of patches, each exhibiting 75



76 nonequilibrium dynamics and together determin- 121
 77 ing the system-level behavior. 122
 78 **Pattern analysis** The procedures with which land- 123
 79 scape pattern is quantified using synoptic indices 124
 80 and spatial statistical methods. 125
 81 **Scale** The spatial or temporal dimension of a phenom- 126
 82 enon in landscape ecology scale usually refers to
 83 grain and extent. Grain is the finest resolution of
 84 a data set in space or time within which homoge-
 85 neity is assumed whereas extent is the total spatial
 86 or temporal expanse of a study.
 87 **Scaling** The translation of information between or
 88 across spatial and temporal scales or organizational
 89 levels.
 90 **Spatial heterogeneity** The discrete or continuous
 91 variations of one or more variables in a landscape,
 92 which can be characterized as patchiness, gradients,
 93 or a mixture of both.
 94 **Spatially explicit models** Models that explicitly take
 95 account of the locations of events in a two- or
 96 three-dimensional space so that not only landscape
 97 composition but also landscape configuration
 98 matters.

Definition of the Subject

100 Landscapes are spatially heterogeneous areas character- 143
 101 ized by diverse patches that differ in size, shape, 144
 102 contents, and history. When spatial heterogeneity is 145
 103 considered, scale matters and hierarchy emerges. Land- 146
 104 scape ecology is the science and art of studying and 147
 105 improving the relationship between spatial pattern and 148
 106 ecological processes on a multitude of scales and 149
 107 organizational levels. In a broad sense, landscape 150
 108 ecology represents both a field of study and 151
 109 a scientific paradigm. As a highly interdisciplinary 152
 110 and transdisciplinary enterprise, landscape ecology 153
 111 integrates biophysical and analytical approaches with 154
 112 humanistic and holistic perspectives across natural and 155
 113 social sciences. Landscape ecology was initially 156
 114 developed in Europe. With theoretical developments 157
 115 in spatial ecology and technological advances in remote 158
 116 sensing and geospatial information processing, land- 159
 117 scape ecology became an internationally recognized 160
 118 field of study in the 1980s. The most salient character- 161
 119 istics of landscape ecology are its emphasis on the 162
 120 pattern-process relationship and its focus on 163

121 broad-scale ecological and environmental issues. Key
 122 research topics in landscape ecology include ecological
 123 flows in landscape mosaics, land use and land cover
 124 change, scaling, relating landscape pattern analysis
 125 with ecological processes, and landscape conservation
 126 and sustainability.

Introduction

127
 128 Landscape ecology is an interdisciplinary field that
 129 aims to understand and improve the relationship
 130 between spatial pattern and ecological processes on
 131 a range of scales [1]. Although the term appeared in
 132 the 1930s, landscape ecology was not a recognized
 133 scientific field of global reach until the 1980s when
 134 remote sensing data and computers became widely
 135 accessible to ecologists and geographers. The 1980s
 136 was also a time period when ecological ideas of
 137 spatial heterogeneity and nonequilibrium dynamics
 138 flourished, and when landscape ecology took roots in
 139 North America. Today, landscape ecology is a
 140 well-established field of study, with active participation
 141 of ecological, geographical, and social scientists from
 142 around the world.

143 Landscape ecology has been dominated by two
 144 schools of thought: the European perspective and the
 145 North American perspective. At the risk of oversimpli-
 146 fication, the European landscape ecology perspective
 147 may be considered as being characterized by a more
 148 holistic, humanistic, and society-centered view, with
 149 a focus on user-inspired and solution-driven research.
 150 The North American landscape ecology perspective, on
 151 the other hand, has been dominated by a more analyt-
 152 ical and biological ecology-centered view, with
 153 a focus on basic science-oriented and question-driven
 154 studies. Cautions must be exercised, however, to avoid
 155 overinterpretation of such dichotomous characteriza-
 156 tion [2]. The two perspectives are neither inclusive nor
 157 exclusive; they are not contradictory but complemen-
 158 tary. There are, and should be, other approaches to
 159 landscape ecology. For example, one may argue for an
 160 Australian landscape ecology perspective that focuses
 161 on pragmatic and functional approaches, typically, tied
 162 with land management, restoration, and conservation
 163 issues (e.g., [3]).

164 Landscape ecology is now a well-established inter-
 165 disciplinary field of study, which is evidenced by several

166 characteristics. These include an evolving but
167 identifiable system of concepts, theories, principles,
168 methods, and applications, a hierarchy of professional
169 organizations from the international association
170 to local chapters, a flagship journal ([http://www.
171 springerlink.com/content/0921-2973](http://www.springerlink.com/content/0921-2973)), the adoption
172 in educational and training programs by major
173 universities and research institutes around the world,
174 and an increasing number of publications in main-
175 stream scientific journals which indicate its recognized
176 status as well as its expanding impacts on related
177 disciplines.

178 In this entry, I focus on the key concepts, research
179 topics, and quantitative methods in landscape ecology.
180 A number of textbooks on landscape ecology are
181 available where more details on the contents covered
182 here can be found [4–8].

183 **What is Landscape Ecology?**

184 **Diverse Concepts of Landscape**

185 The term, “landscape,” is a key concept in a number of
186 fields, from social to geographical and ecological
187 sciences. With the rise of landscape ecology in the
188 past several decades, the concept of landscape has
189 achieved a prominent status in the interdisciplinary
190 literature. However, because of the plurality of its
191 origins and interpretations, landscape has acquired
192 various connotations. For example, the same word
193 may refer to a natural landscape, a cultural landscape,
194 a political landscape, an economic landscape, a mental
195 landscape, an adaptive landscape, a landscape view,
196 landscaping, or landscape painting [9, 10].

197 Even within the field of landscape ecology, the
198 word, “landscape,” has different meanings, and the
199 differences usually hinge on the spatial scale and
200 the contents of a landscape. For example, landscape
201 has been defined as a kilometers-wide geographic area
202 [11, 12], which corresponds to the “human-scale”
203 landscape. This is the scale at which the field of
204 landscape ecology was originally developed in Europe,
205 and at which most landscape studies have been
206 conducted around the world ever since. The human-
207 scale landscape, in general, seems to coincide well with
208 geographic units such as watersheds and urban
209 regions [4], as well as spatial domains of human

210 perception [13]. Thus, it resonates with the public,
211 the decision makers, and researchers who are conscious
212 about the environmental setting in which they live,
213 work, and engage in recreation.

214 Many other landscape ecologists, however, have
215 treated landscape as a multi-scale or hierarchical con-
216 cept, meaning that a landscape is a spatially heteroge-
217 neous area that may be of various sizes, depending on
218 the subject of study and the research questions at hand
219 [6, 14, 15]. In this case, landscape is an “ecological
220 criterion” [14], and its essence does not lie in its
221 absolute scale but in its internal heterogeneity.
222 Different plant and animal species perceive, experience,
223 and respond to spatial heterogeneity at different
224 scales, and patterns and processes in landscapes tend
225 to have different characteristic scales [16]. Thus,
226 a hierarchical concept of landscape, of course also
227 encompassing the human-scale, is both sensible and
228 necessary. Apparently, one does not need to consider
229 a landscape of tens of square kilometers to study how
230 grassland vegetation pattern affects the movement of
231 beetles [17] or is affected by gophers [18].

232 The contents that constitute a landscape vary
233 greatly in landscape ecological research. For simplicity,
234 the components of a landscape may be classified as
235 tangible versus intangible and biophysical versus cul-
236 tural. This is not intended to represent a dichotomous
237 view, but rather a continuum within which a variety of
238 components coexist. Tress and Tress [10] proposed a
239 “transdisciplinary landscape concept” that encom-
240 passes five dimensions: (1) landscape as a spatial entity,
241 (2) landscape as a mental entity, (3) landscape as
242 a temporal dimension, (4) landscape as a nexus of
243 nature and culture, and (5) landscape as a complex
244 system. Landscape ecological studies often have
245 focused on some but not all of these dimensions.
246 The concept of landscape provides a meeting ground
247 for a number of disciplines, including archaeology,
248 ecology, geography, geology, history, landscape
249 architecture, and regional economics. To achieve its
250 interdisciplinary and transdisciplinary goals, landscape
251 ecology needs to appreciate and integrate the multifac-
252 eted perspectives on the culture-nature/people-place
253 relationships that are offered by these diverse
254 disciplines.

255 Evolving Concepts of Landscape Ecology

256 The definitions of landscape ecology are also diverse,
257 although they are not quite as numerous as those of
258 landscape (Table 1). Images can be powerfully
259 inspiring, and this is especially true to someone who
260 has a special interest in landscape patterns. Partly
261 inspired by the conspicuous spatial patterns revealed
262 in aerial photographs, the German geographer and
263 botanist Carl Troll [19] coined the term “landscape
264 ecology” and defined it later as “the study of the main
265 complex causal relationships between the life commu-
266 nities and their environment in a given section of
267 a landscape” [20, 21]. Carl Troll’s training and research
268 in multiple disciplines endowed him with the abilities
269 to synthesize across, and innovate at the interface
270 between, different fields. He was trained as a botanist;
271 did his doctoral dissertation in plant physiology; and
272 then spent decades working on the climatic, geologic,
273 geographical, and ecological aspects of various
274 landscapes in Europe, South America, and Africa. It is
275 not difficult to understand why Troll could simulta-
276 neously appreciate the then-new idea of “ecosystem”
277 put forward by Arthur Tansley [28], as well as the
278 great potential for geospatial analysis presented by
279 aerophotography. As a result of his attempt to
280 integrate the “vertical” ecological approach with the
281 “horizontal” geographical approach, a new field of
282 study was born.

283 In the past several decades, landscape ecology has
284 acquired a number of definitions which all are, in some
285 way, related to Carl Troll’s original definition. For
286 example, Zonneveld [22] defined landscape ecology as
287 “an aspect of geographical study which considers the
288 landscape as a holistic entity, made up of different
289 elements, all influencing each other.” He advocated
290 that the landscape should be studied as the “total
291 character of a region,” not “in terms of the
292 separate aspects of its component elements” [22, 29].
293 This holistic landscape perspective continues and
294 culminates in the work by Naveh [30], who described
295 landscape ecology as the study of “the total spatial
296 and functional entity of natural and cultural living
297 space.”

298 Some key ideas of contemporary landscape ecology,
299 such as patch dynamics [31–33] and the patch-corridor-
300 matrix model [11, 12], began to emerge in

North America in the late 1970s, apparently with little
connection to the European root. The early ideas of
landscape ecology in North America were inspired by
the theory of island biogeography [34], with an explicit
focus on spatial heterogeneity. The first major commu-
nication between North American and European
landscape ecologists occurred in 1981 when five
American ecologists attended the first International
Congress on Landscape Ecology in the Netherlands.
Two years later, 25 ecologists (23 Americans,
1 Canadian, and 1 French) gathered at Allerton
Park, Illinois of USA, to discuss the nature and future
directions of landscape ecology. The report of this
historic work, published in the following year [24],
became an important guide to the incipient landscape
ecologists in North America [35].

Why was such discussion necessary after landscape
ecological research had been practiced for more than
40 years in Europe? The answer seems clear from
Forman [36]: “What theory explains the spatial hetero-
geneity of energy, nutrients, water, plants, and animals
at the level of a landscape, the setting in which we live?
Alas, none.” To develop such a landscape theory,
broader scales that encompass multiple ecosystems
need to be considered, and horizontal interactions
have to be a focus of study. Thus, Forman and Godron
[11, 12] defined landscape ecology as the study of the
structure (spatial relationships among the distinctive
landscape elements), function (flows of energy,
materials, and species among landscape elements),
and dynamics (temporal change in landscape structure
and function) of landscapes. The main theme of
landscape ecology in North America, with an unmis-
takable focus on spatial heterogeneity, was set in
Risser et al. [24]:

- ▶ Landscape ecology focuses explicitly upon spatial
pattern. Specifically, landscape ecology considers the
development and dynamics of spatial heterogeneity,
spatial and temporal interactions and exchanges across
heterogeneous landscapes, influences of spatial het-
erogeneity on biotic and abiotic processes, and
management of spatial heterogeneity.

Is landscape ecology a subdiscipline of ecology?
The term itself apparently suggests that it is. Many
ecologists do consider landscape ecology as a branch
of ecology (e.g., [6]), and most ecology programs of

347 major research universities worldwide now offer
 348 courses in landscape ecology. On the other hand,
 349 Zonneveld [22] indicated that landscape ecology is
 350 not part of biological sciences, but a branch of geogra-
 351 phy. Risser et al. [24] contemplated three ways in which
 352 landscape ecology may be viewed: as an intersection of
 353 many disciplines, as a separate discipline, or as a branch
 354 of ecology. They concluded that only the first option
 355 was “intellectually and practically the most persuasive.”
 356 They further pointed out that “viewing landscape
 357 ecology as an interdisciplinary field of research avoids
 358 the issue of which discipline ‘owns’ landscape ecology”
 359 (a problem that may have hindered the healthy devel-
 360 opment of some interdisciplinary fields, such as human
 361 ecology, for which geography, sociology, and anthro-
 362 pology all have claimed ownership). The Allerton
 363 workshop report clearly recognized the importance
 364 of the multidimensionality of landscapes and the
 365 cross-disciplinarity of landscape ecology:

366 ▶ A major forcing function of landscapes is the activity of
 367 mankind, especially associated cultural, economic, and
 368 political phenomena. . . . Landscape ecology is not
 369 a distinct discipline or simply a branch of ecology, but
 370 rather is the synthetic intersection of many related
 371 disciplines that focus on the spatial-temporal pattern
 372 of the landscape” [24].

373 Today, a general consensus seems to have emerged
 374 that landscape ecology is not simply an academic
 375 discipline, but rather a highly interdisciplinary field of
 376 study [2, 37]. Landscape ecology is an interdisciplinary
 377 and transdisciplinary science that focuses on the
 378 relationship between spatial pattern and ecological
 379 processes across scales. The goal of landscape ecology
 380 is not only to understand this relationship but also to
 381 influence it so as to help achieve landscape sustainabil-
 382 ity [38–40]. As such, a pluralistic and hierarchical
 383 framework has been proposed to facilitate synergistic
 384 interactions between biophysical/pattern-process
 385 and holistic/humanistic perspectives (Fig. 1) [37, 38].
 386 “Hierarchical” here refers to the varying degrees of
 387 cross-disciplinary, the hierarchy of organizational
 388 levels, and the multiplicity of spatiotemporal scales of
 389 landscape ecological studies. “Pluralistic” indicates the
 390 necessity and importance of recognizing and valuing
 391 the different perspectives and methods in landscape
 392 ecology due to its diverse origins and goals.

Key Research Topics Landscape Ecology 393

Based on the suggestions by a group of leading landscape 394
 ecologists (Table 2), Wu and Hobbs [2] identified six 395
 key issues that characterize landscape ecology: (1) inter- 396
 disciplinary or transdisciplinarity, (2) integration 397
 between basic research and applications, (3) Concep- 398
 tual and theoretical development, (4) education and 399
 training, (5) international scholarly communication 400
 and collaborations, and (6) outreach and communica- 401
 tion with the public and decision makers. Wu and 402
 Hobbs [2] also summarized ten key research topics 403
 and priorities as follows: 404

1. Ecological flows in landscape mosaics: A primary 405
 goal of landscape ecology is to understand the 406
 reciprocal relationship between spatial pattern 407
 and ecological processes [14]. Understanding the 408
 mechanisms of flows of organisms, energy, 409
 material, and information in landscape mosaics 410
 is central to landscape ecology. In particular, the 411
 study of the effects of spatial pattern on 412
 population and ecosystem processes has made 413
 much progress in the past several decades. There 414
 is a need to integrate socioeconomic theory of 415
 landscape change into metapopulation models to 416
 make them more relevant to the issues of biodi- 417
 versity conservation and landscape sustainability. 418
 The spread of invading species has become an 419
 increasingly important ecological and economic 420
 problem which deserves more research efforts. 421
2. Causes, processes, and consequences of land use 422
 and land cover change: Land use and land cover 423
 change is arguably the most important driver for 424
 changes in the structure and function of land- 425
 scapes. Land use and land cover change is driven 426
 primarily by socioeconomic forces, and is one of 427
 the most important and challenging research areas 428
 in landscape ecology. Numerous studies have been 429
 carried out to investigate the effects of land 430
 use and land cover change on biodiversity and 431
 ecological flows in human-dominated landscapes. 432
 More research efforts are needed to incorporate 433
 the insights of economic geography which studies 434
 how economic activity is distributed in space and 435
 resource economics which determines how land 436
 will be used [41]. Long-term landscape changes 437
 induced by economic activities and climate 438

- change, as well as “land use legacies” (i.e., the types, extents, and durations of persistent effects of prior land use on ecological patterns and processes) need to be emphasized in future research.
3. Nonlinear dynamics and landscape complexity: Landscapes are spatially extended complex systems which exhibit emergent properties, phase transitions, and threshold behavior. To understand the complexity of landscapes, concepts and methods from the science of complexity and nonlinear dynamics should be helpful. For example, self-organization, percolation theory, complex adaptive systems (CAS), fractal geometry, cellular automata, and genetic algorithms have been used in the study of spatiotemporal dynamics of landscapes (e.g., [42–46]). However, the theoretical potential and practical implications of these concepts and methods are yet to be fully explored.
 4. Scaling: Scaling refers to the translation of information from one scale to another across space, time, or organizational levels. Spatial scaling, in particular, is essential in both the theory and practice of landscape ecology because spatial heterogeneity does not make any sense without the consideration of scale [47]. While scale effects are widely recognized in landscape ecology, scaling-up or scaling-down across heterogeneous landscapes remains a grand challenge in landscape ecology and beyond [48]. General rules and pragmatic methods for scaling landscape patterns and processes need to be developed and tested.
 5. Methodological advances: Landscape variables are often spatially autocorrelated and spatially dependent, which poses serious challenges for using traditional statistical methods based on the assumption of independence of observations. The spatial autocorrelation and dependence that traditional statistical methods try to get rid of are usually what landscape analyses intend to get at. Thus, spatial statistical methods that directly deal with spatial autocorrelation and dependence have increasingly been used in landscape ecology. Also, most landscape ecological problems need to be studied over large and multiple scales in a spatially explicit manner. This need poses problems such as the lack of replicability or “pseudoreplication” [49]. To get to the processes and mechanisms of landscape phenomena, landscape ecology has developed a suite of spatially explicit modeling approaches [50, 51]. In both spatial analysis and modeling of landscapes, remote sensing and GIS (geographic information systems) have become indispensable.
 6. Relating spatial pattern measures to ecological processes: To understand the relationship between pattern and process, quantifying landscape pattern is necessary. Indeed, landscape pattern analysis has been a major part of landscape ecological research for the last few decades. A number of landscape metrics (Table 3) and spatial statistical methods have been developed and applied for describing and comparing the spatial patterns of landscapes, monitoring and predicting changes in landscape patterns, and relating spatial pattern to ecological processes at a particular scale or across a range of scales [47, 53, 54]. Nevertheless, a sound ecological understanding of these spatial analysis methods is yet to be fully developed [55].
 7. Integrating humans and their activities into landscape ecology: Socioeconomic processes are the primary drivers for land use and land cover change which in turn determines the structure, function, and dynamics of most landscapes. Social and economic processes have increasingly been integrated into landscape ecological studies. The need for incorporating humans, including their perceptions, value systems, cultural traditions, and socioeconomic activities, into landscape ecology has made it a highly interdisciplinary and transdisciplinary enterprise [38, 56]. That said, effectively integrating human-related processes into ecology may remain one of the ultimate challenges for landscape ecologists in years to come.
 8. Optimization of landscape pattern: If spatial pattern significantly influences ecological flows in the landscape, then there must be certain patterns that are better than others. This is a question of landscape pattern optimization (e.g., optimization of land use pattern, optimal landscape management, optimal landscape design, and planning). For example, can landscape patterns be optimized in terms of both the composition and configuration of patches and matrix

533 characteristics to maximize biodiversity and
 534 ecosystem services? Are there optimal ways of
 535 “spatially meshing nature and culture” to promote
 536 landscape sustainability? These are some of the
 537 challenging questions that landscape ecologists
 538 ought to address now and in the future. Spatial
 539 optimization of landscape pattern for ecological
 540 processes presents exciting research opportunities
 541 and requires interdisciplinary approaches.

542 9. Landscape conservation and sustainability:
 543 Biodiversity, ecosystem functions, and human
 544 activities, all take place in landscapes. Landscape
 545 fragmentation profoundly alters ecological and
 546 socioeconomic processes. Thus, the importance
 547 of applying landscape ecological principles in
 548 biodiversity conservation and sustainable devel-
 549 opment has been increasingly recognized.
 550 However, specific landscape ecological guidelines
 551 for biodiversity conservation are needed, and
 552 a comprehensive and operational definition of
 553 landscape sustainability is yet to be developed.

554 10. Data acquisition and accuracy assessment: Land-
 555 scape ecological studies use large-scale and multi-
 556 scale data. A suite of advanced technologies are
 557 readily available, including various remote sensing
 558 techniques, GIS, GPS (global positioning systems),
 559 and spatial analysis and modeling approaches.
 560 However, ecological understanding of species and
 561 ecosystems is essential in landscape ecology, and
 562 this requires the collection of basic biological data
 563 of landscapes. Also, to ensure the quality of
 564 landscape data, error analysis, uncertainty analysis,
 565 and accuracy assessment have become a key issue in
 566 landscape ecological research.

567 **Future Directions**

568 Landscape ecology is a highly interdisciplinary field of
 569 study which is characterized, most conspicuously, by its
 570 spatial explicitness in dealing with ecological problems
 571 in theory and practice. Emphasis on spatial heterogene-
 572 ity begs questions of the pattern-process relationships
 573 and scale. Studying spatial pattern without relating it to
 574 ecological processes is superficial, and investigating eco-
 575 logical processes without consideration of spatial pattern
 576 is incomplete. From this perspective, landscape ecology

577 is a science of heterogeneity and scale, providing a new
 578 scientific paradigm for ecology and other related fields.

579 On the other hand, with increasing human domi-
 580 nance in the biosphere, emphasis on broad spatial
 581 scales makes it inevitable to deal with humans and
 582 their activities. As a consequence, humanistic and
 583 holistic perspectives have been and will continue to
 584 be central in landscape ecological research. Thus,
 585 landscape ecology has become increasingly relevant to
 586 sustainability research and practice [38, 56]. First, land-
 587 scape ecology provides a hierarchical and integrative
 588 ecological basis for dealing with issues of biodiversity
 589 and ecosystem functioning from fine to broad scales.
 590 Second, landscape ecology has already developed
 591 a number of holistic and humanistic approaches to
 592 studying nature–society interactions. Third, landscape
 593 ecology offers theory and methods for studying the
 594 effects of spatial configuration of biophysical and
 595 socioeconomic component on the sustainability of a
 596 place. Fourth, landscape ecology has developed a suite
 597 of pattern metrics and indicators which can be used for
 598 quantifying sustainability in a geospatially explicit
 599 manner. Finally, landscape ecology provides both
 600 theoretical and methodological tools for dealing with
 601 scaling and uncertainty issues that are fundamental to
 602 most nature–society interactions.

603 To move forward, future landscape ecological stud-
 604 ies need to further address the key research topics as
 605 discussed earlier in this entry. In addition, concerted
 606 efforts need to be made to focus on sustainability-
 607 related research questions. For example, what theories,
 608 principles, and methods of landscape ecology are
 609 pertinent to sustainability and how can they be
 610 operationalized? How does landscape pattern or spatial
 611 heterogeneity affect sustainability? How do ecological,
 612 economic, and social patterns and processes in land-
 613 scapes change with scale and interact to influence sus-
 614 tainability? How is landscape sustainability measured
 615 and what roles can landscape metrics play in all this?
 616 How can landscape models to project sustainability
 617 trajectories in response to environmental, economic,
 618 social, and institutional changes be developed?
 619 And finally, how can landscape ecology help design
 620 sustainable landscapes?

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t1.1 **Landscape Ecology. Table 1** A list of definitions of landscape ecology

	Definition	Source
t1.2	The German geographer Carl Troll coined the term "landscape ecology" in 1939, and defined it in 1968 as "the study of the main complex causal relationships between the life communities and their environment in a given section of a landscape. These relationships are expressed regionally in a definite distribution pattern (landscape mosaic, landscape pattern) and in a natural regionalization at various orders of magnitude" (Troll 1968; cited in Troll 1971)	<ul style="list-style-type: none"> • Troll [19] • Troll [20] • Troll [21]
t1.3	"Landscape ecology is an aspect of geographical study which considers the landscape as a holistic entity, made up of different elements, all influencing each other. This means that land is studied as the 'total character of a region', and not in terms of the separate aspects of its component elements" (Zonneveld 1972)	<ul style="list-style-type: none"> • Zonneveld [22]
t1.4	"Landscape ecology is a young branch of modern ecology that deals with the interrelationship between man and his open and built-up landscapes" based on general systems theory, biocybernetics, and ecosystemology (Naveh and Liberman 1984). "Landscapes can be recognized as tangible and heterogeneous but closely interwoven natural and cultural entities of our total living space," and landscape ecology is "a holistic and transdisciplinary science of landscape study, appraisal, history, planning and management, conservation, and restoration" (Naveh and Liberman 1994)	<ul style="list-style-type: none"> • Naveh and Lieberman [5] • Naveh and Lieberman [23]
t1.5	"A landscape is a kilometers-wide area where a cluster of interacting stands or ecosystems is repeated in similar form; landscape ecology, thus, studies the structure, function and development of landscapes" (Forman 1981). Landscape structure refers to "the spatial relationships among the distinctive ecosystems;" landscape function refers to "the flows of energy, materials, and species among the component ecosystems;" and landscape change refers to "the alteration in the structure and function of the ecological mosaic over time" (Forman and Godron 1986).	<ul style="list-style-type: none"> • Forman [11] • Forman [12]
t1.6	"Landscape ecology focuses explicitly upon spatial pattern. Specifically, landscape ecology considers the development and dynamics of spatial heterogeneity, spatial and temporal interactions and exchanges across heterogeneous landscapes, influences of spatial heterogeneity on biotic and abiotic processes, and management of spatial heterogeneity" (Risser et al. 1984). "Landscape ecology is not a distinct discipline or simply a branch of ecology, but rather is the synthetic intersection of many related disciplines that focus on the spatial-temporal pattern of the landscape" (Risser et al. 1984).	<ul style="list-style-type: none"> • Risser et al. [24]
t1.7	"Landscape ecology emphasizes broad spatial scales and the ecological effects of the spatial patterning of ecosystems" (Turner 1989).	<ul style="list-style-type: none"> • Turner [25]
t1.8	"Landscape ecology is the study of the reciprocal effects of the spatial pattern on ecological processes," and "concerns spatial dynamics (including fluxes of organisms, materials, and energy) and the ways in which fluxes are controlled within heterogeneous matrices" (Pickett and Cadenasso 1995).	<ul style="list-style-type: none"> • Pickett and Cadenasso [14]
t1.9	"Landscape ecology investigates landscape structure and ecological function at a scale that encompasses the ordinary elements of human landscape experience: yards, forests, fields, streams, and streets" (Nassauer 1997).	<ul style="list-style-type: none"> • Nassauer [26]
t1.10	Landscape ecology is "ecology that is spatially explicit or locational; it is the study of the structure and dynamics of spatial mosaics and their ecological causes and consequences" and "may apply to any level of an organizational hierarchy, or at any of a great many scales of resolution" (Wiens 1999).	<ul style="list-style-type: none"> • Wiens [27]

Landscape Ecology. Table 1 (Continued)

	Definition	Source
t1.12	"Landscape ecology emphasizes the interaction between spatial pattern and ecological process, that is, the causes and consequences of spatial heterogeneity across a range of scales" (Turner et al. 2001). "Two important aspects of landscape ecology . . . distinguish it from other subdisciplines within ecology": "First, landscape ecology explicitly addresses the importance of spatial configuration for ecological processes" and "second, landscape ecology often focuses on spatial extents that are much larger than those traditionally studied in ecology, often, the landscape as seen by a human observer" (Turner et al. 2001).	<ul style="list-style-type: none">• Turner [6]
t1.13	"Landscape ecology is the science and art of studying and influencing the relationship between spatial pattern and ecological processes across hierarchical levels of biological organization and different scales in space and time."	<ul style="list-style-type: none">• Wu and Hobbs [1]

Galley Proof



t2.1 **Landscape Ecology. Table 2** A list of major research topics in landscape ecology suggested by a group of leading landscape ecologists from around the world at the 16th Annual Symposium of the US Regional Association of the International Association for Landscape Ecology, held at Arizona State University, Tempe, in April 2001 [2]

t2.2	Development of theory and principles	<ul style="list-style-type: none"> • Landscape mosaics and ecological flows • Land transformations • Landscape sustainability • Landscape complexity
t2.3	Landscape metrics	<ul style="list-style-type: none"> • Norms or standards for metric selection, change detection, etc. • Integration of metrics with holistic landscape properties • Relating metrics to ecological processes • Sensitivity to scale change
t2.4	Ecological flows in landscape mosaics	<ul style="list-style-type: none"> • Flows of organisms, material, energy, and information • Effects of connectivity, edges, and boundaries • Spread of invading species • Spatial heterogeneity and ecosystem processes • Disturbances and patch dynamics
t2.5	Optimization of landscape pattern	<ul style="list-style-type: none"> • Optimization of land use pattern • Optimal management • Optimal design and planning • New methods spatial optimization
t2.6	Metapopulation theory	<ul style="list-style-type: none"> • Integration of the view of landscape mosaics • Integration of economic theory of land use change and cellular automata
t2.7	Scaling	<ul style="list-style-type: none"> • Extrapolating information across heterogeneous landscapes • Development of scaling theory and methods • Derivation of empirical scaling relations for landscape pattern and processes
t2.8	Complexity and nonlinear dynamics of landscapes	<ul style="list-style-type: none"> • Landscapes as spatially extended complex systems • Landscapes as complex adaptive systems • Thresholds, criticality, and phase transitions • Self-organization in landscape structure and dynamics
t2.9	Land use and land cover change	<ul style="list-style-type: none"> • Biophysical and socioeconomic drivers and mechanisms • Ecological consequences and feedbacks • Long-term landscape changes driven by economies and climate changes
t2.10	Spatial heterogeneity in aquatic systems	<ul style="list-style-type: none"> • The relationship between spatial pattern and ecological processes in lakes, rivers, and oceans • Terrestrial and aquatic comparisons
t2.11	Landscape-scale experiments	<ul style="list-style-type: none"> • Experimental landscape systems • Field manipulative studies • Scale effects in experimental studies
t2.12	New methodological developments	<ul style="list-style-type: none"> • Integration among observation, experimentation, and modeling • New statistical and modeling methods for spatially explicit studies • Interdisciplinary and transdisciplinary approaches
t2.13	Data collection and accuracy assessment	<ul style="list-style-type: none"> • Multiple-scale landscape data • More emphasis on collecting data on organisms and processes • Data quality control • Metadata and accuracy assessment
t2.14	Fast changing and chaotic landscapes	<ul style="list-style-type: none"> • Rapidly urbanizing landscapes • War zones • Other highly dynamic landscapes

Landscape Ecology. Table 2 (Continued)

t2.15	Landscape sustainability	<ul style="list-style-type: none">• Developing operational definitions and measures that integrate ecological, social, cultural, economic, and aesthetic components• Practical strategies for creating and maintaining landscape sustainability
t2.16	Human activities in landscapes	<ul style="list-style-type: none">• The role of humans in shaping landscape pattern and processes• Effects of socioeconomic and cultural processes on landscape structure and functioning
	Holistic landscape ecology	<ul style="list-style-type: none">• Landscape ecology as an anticipative and prescriptive environmental science• Development of holistic and systems approaches

Galley Proof



t3.1 **Landscape Ecology. Table 3** Some commonly used landscape metrics [4, 52]

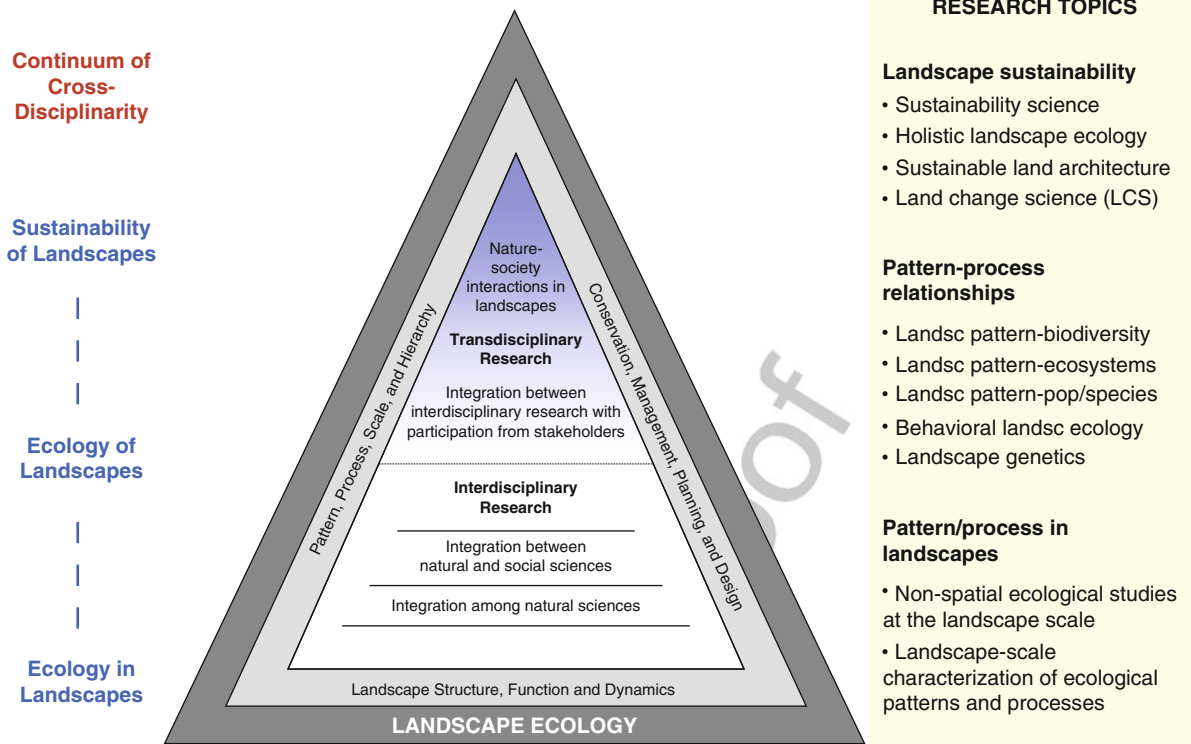
	Landscape metric	Abbreviation	Description
t3.2	Patch shape index	PSI	A measure of the shape complexity of an individual patch: $PSI = \frac{P}{2\sqrt{A\pi}}$ where P is the perimeter of a patch, and A is the area of the patch. $D = 1$ for circles; $D = 1.1283$ for squares; and $D = 1.1968$ for a rectangle ($2 L$ by L). $1/D$ is called "compactness" (see Forman [4]).
t3.3	Perimeter/area ratio	PAR	A measure of the shape complexity of an individual patch: $PAR = P/A$ where P is the perimeter of a patch, and A is the area of the patch.
t3.4	Number of patches	NP	The total number of patches in the landscape.
t3.5	Patch density	PD	The number of patches per square kilometer (i.e., 100 ha).
t3.6	Total edge	TE	The sum of the lengths of all edge segments (unit: meter).
t3.7	Edge density	ED	The total length of all edge segments per hectare for the class or landscape of consideration (unit: m/ha).
t3.8	Patch richness	PR	The number of different patch types in the landscape.
t3.9	Patch richness density	PRD	The number of patch types per square kilometer (or 100 ha).
t3.10	Shannon's diversity index	SHDI	A measure of patch diversity in a landscape that is determined by both the number of different patch types and the proportional distribution of area among patch types: $H = - \sum_{i=1}^m p_i \ln(p_i)$ where m is the total number of patch types and p_i is the proportion of the landscape area occupied by patch type i .
t3.11	Dominance index	D	A measure of the degree of dominance by one or a few patch types in a landscape: $D = H_{\max} + \sum_{i=1}^m p_i \ln p_i$ where H_{\max} is the maximum diversity when all patch types are present in equal proportions, m is the total number of patch types, and p_i is the proportion of the landscape area occupied by patch type i . Small values of D tend to indicate that landscapes with numerous land use types of similar proportions.
t3.12	Largest patch index	LPI	The ratio of the area of the largest patch to the total area of the landscape (unit: percentage).
t3.13	Mean patch size	MPS	The average area of all patches in the landscape (unit: ha).
t3.14	Patch size standard deviation	PSSD	The standard deviation of patch size in the entire landscape (unit: ha).
t3.15	Patch size coefficient of variation	PSCV	The standard deviation of patch size divided by mean patch size for the entire landscape (unit: percentage).
t3.16	Landscape shape index	LSI	A modified perimeter/area ratio of the form: $LSI = \frac{0.25E}{\sqrt{A}}$ where E is the total length of patch edges and A is the total area of the landscape (unitless).
t3.17			

Au2

Landscape Ecology. Table 3 (Continued)

Landscape metric	Abbreviation	Description
t3.18 Mean patch shape index	MSI	A patch-level shape index averaged over all patches in the landscape: $MSI = \frac{\sum_{i=1}^m \sum_{j=1}^n \left[\frac{0.25P_{ij}}{\sqrt{a_{ij}}} \right]}{N}$ where P_{ij} and a_{ij} are the perimeter and area of patch ij , respectively, and N is the total number of patches in the landscape (unitless).
t3.19 Area-weighted mean patch shape index	AWMSI	Mean patch shape index weighted by relative patch size: $AWMSI = \sum_{i=1}^m \sum_{j=1}^n \left[\left(\frac{0.25P_{ij}}{\sqrt{a_{ij}}} \right) \left(\frac{a_{ij}}{A} \right) \right]$ where P_{ij} and a_{ij} are the perimeter and area of patch ij , respectively, A is the total area of the landscape, m is the number of patch types, and n is the total number of patches of type i (unitless).
t3.20 Double-log fractal dimension	DLFD	The fractal dimension for the entire landscape which is equal to 2 divided by the slope of the regression line between the logarithm of patch area and the logarithm of patch perimeter: $DLFD = \frac{2}{\frac{\left[N \sum_{i=1}^m \sum_{j=1}^n (\ln(P_{ij}) \ln(a_{ij})) \right] - \left[\left(\sum_{i=1}^m \sum_{j=1}^n \ln(a_{ij}) \right) \right]}{\left(N \sum_{i=1}^m \sum_{j=1}^n (\ln(P_{ij}^2)) \right) - \left(\sum_{i=1}^m \sum_{j=1}^n \ln(P_{ij}) \right)^2}}$ where P_{ij} and a_{ij} are the perimeter and area of patch ij , respectively, m is the number of patch types, n is the total number of patches of type i , and N is the total number of patches in the landscape (unitless).
t3.21 Mean patch fractal dimension	MPFD	The average fractal dimension of individual patches in the landscape, which is the summation of fractal dimension for all patches divided by the total number of patches in the landscape: $FD = \frac{\sum_{i=1}^m \sum_{j=1}^n \left(\frac{2 \ln(0.25P_{ij})}{\ln(a_{ij})} \right)}{N}$ where P_{ij} and a_{ij} are the perimeter and area of patch ij , respectively, m is the number of patch types, n is the total number of patches of type i , and N is the total number of patches in the landscape (unitless).
t3.22 Area-weighted mean patch fractal dimension	AWMPFD	The patch fractal dimension weighted by relative patch area: $AWMPFD = \sum_{i=1}^m \sum_{j=1}^n \left(\frac{2 \ln(0.25P_{ij})}{\ln(a_{ij})} \right) \left(\frac{a_{ij}}{A} \right)$ where P_{ij} and a_{ij} are the perimeter and area of patch ij , respectively, m is the number of patch types, n is the total number of patches of type i , and A is the total area of the landscape (unitless).
t3.23 Contagion	CONT	An information theory-based index that measures the extent to which patches are spatially aggregated in the landscape (Li and Reynolds 1993): $CONT = \left[1 + \sum_{i=1}^m \sum_{j=1}^m p_{ij} \ln(p_{ij}) / 2 \ln(m) \right] (100)$ where p_{ij} is the probability that two randomly chosen adjacent pixels belong to patch type i and j , m is the total number of patch types in the landscape (unitless).

Au3



Landscape Ecology. Figure 1

A schematic representation of a hierarchical and pluralistic view of landscape ecology (Modified from [38])

Author Query Form

Encyclopedia of Sustainability Science and Technology
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Query Refs.	Details Required	Author's response
AU1	Kindly provide index terms.	
AU2	Variables "E", "A", "P _{ij} ", "N", etc., are found in both roman and italics in the text and in equations. Please confirm which form has to be made consistent.	
AU3	"Li and Reynolds 1993" is cited in the text but missing in the reference list. Kindly include it in the reference list.	
AU4	The following duplicate references have been deleted. Please check. "Naveh and Lieberman (1994); Wu and Hobbs (2007)".	