Scientific Foundations and Problem-Driven Case Studies of Landscape Sustainability:
Sustainability of Human-Environment Systems Through the Lens of the Landscape

by

Bingbing Zhou

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved April 2020 by the
Graduate Supervisory Committee:

Jianguo Wu, Chair
Rimjhim Aggarwal
John M. Anderies
Marcus A. Janssen
Billie L. Turner II

ARIZONA STATE UNIVERSITY

May 2020
ABSTRACT

The science community has made efforts for over a half century to address sustainable development, which gave birth to sustainability science at the turn of the twenty-first century. Along with the development of sustainability science during the past two decades, a landscape sustainability science (LSS) perspective has been emerging. As interests in LSS continue to grow rapidly, scholars are wondering what LSS is about and how LSS fits into sustainability science, while practitioners are asking how LSS actually contributes to sustainability in the real world. To help address these questions, this dissertation research aims to explore the currently underused problem-driven, diagnostic approach to enhancing landscape sustainability through an empirical example of urbanization-associated farmland loss (UAFL). Based mainly on multimethod analysis of bibliographic information, the dissertation explores conceptual issues such as how sustainability science differs from conventional sustainable development research, and how the past, present, and future research needs of LSS evolve. It also includes two empirical studies diagnosing the issue of urban expansion and the related food security concern in the context of China, and proposes a different problem framing for farmland preservation such that stakeholders can be more effectively mobilized. The most important findings are: (1) Sustainability science is not “old wine in a new bottle,” and in particular, is featured by its complex human-environment systems perspective and value-laden transdisciplinary perspective. (2) LSS has become a vibrant emerging field since 2004-2006 with over three-decade’s intellectual accumulation deeply rooted in landscape ecology, yet LSS has to further embrace the two featured perspectives of sustainability science and to conduct more problem-driven, diagnostic
studies of concrete landscape-relevant sustainability concerns. (3) Farmland preservationists’ existing problem framing of UAFL is inappropriate for its invalid causal attribution (i.e., urban expansion is responsible for farmland loss; farmland loss is responsible for decreasing grain production; and decreasing grain production instead of increasing grain demand is responsible for grain self-insufficiency); the real problem with UAFL is social injustice due to collective action dilemma in preserving farmland for regional and global food sufficiency. The present research provides broad implications for landscape scientists, the sustainability research community, and UAFL stakeholders.
This dissertation is dedicated to Cyrus Chung-Ying Tang (January 9, 1930–June 23, 2018), a humble, great man who passed away in Las Vegas, NV in my third year of Ph.D. study. In addition to his many other contributions to society through the Cyrus Tang Foundation, “Grandpa Tang” supported more than 10,000 college students in twenty-two top universities of China since 1998. I am so lucky to be a member of the Tang family since 2008, and have been more than privileged to serve as a vice president of the Cyrus Tang Foundation Alumni Association and the head of the overseas chapter during the past two years. He is the role model for hundreds of thousands of people including me, and in my mind, a real sustainability practitioner who left behind a glorious legacy and a growing community to make the world a better place through whatever little things. His legacy and the Tang family gave me the belief, courage, and backup to say “yes” or “no” in many critical decisions, and helped me survive the Ph.D. grind.
ACKNOWLEDGMENTS

I must thank Professor Jianguo Wu for taking the big trouble of serving as my major supervisor and committee chair, and for three things in particular. Firstly, without his help in getting me into this unique Sustainability Ph.D. program, I would most likely have ended up elsewhere and would not have experienced the many good things at ASU. Secondly, without his providing a few semesters’ RAship and also his support of my applications for other funding, I would not have been able to finish the degree. Thirdly, with the five years’ observing his being a well-known scholar and with the close interactions with him, I have learned many things, e.g., how the academia works and his incisive historical perspective on doing science. Besides, Prof. Wu has provided me with many other resources or opportunities in especially the last two years.

I must thank Professors Rimjhim Aggarwal, Marty Anderies, Marco Janssen, and B. L. Turner II for their kindly serving on my committee, and for their profound influences on my research. For example, during 2016, Marco led me all the way into the Ostromian intellectual world, and also provided me with a clear methodological landscape of sustainability research. The bibliometric methods he introduced to me made the second and third chapters possible. Marco has always been unconditionally supportive and constructively critical, more than I could ever expect from a committee member. In spring 2017, with timely help from Rimjhim, I succeeded in competing for the Neely Foundation Food and Agriculture Sustainability Research Grant, which together with the matchup funding of my collaborator in China provided the data for my fourth chapter. Marty’s work gave me a good sense of elegant research taste and provided me with a clear theoretical foundation of sustainability. In fall 2018, Marty kindly helped with my
long-stagnated third chapter. I am deeply indebted to Professor Turner for especially his tremendous help with my long-stagnated second chapter in summer and fall 2019. I was so impressed by his rigor and timely fashion as a co-author, his emphasis on problem entry and framing, and how he as a great scientist writes papers.

I owe many thanks to the administrative team of our school, especially Katie Ulmer, Lisa Murphy, Lindsey Plait Jones, and Ivy Gerbis. I have encountered many great teachers in ASU, such as Dr. Sonja Klinsky, Dr. Kelli Larson, Dr. Joshua Abbott, Dr. Charles Perrings, Kathryn Kyle, and Loretta Doemland. I must also thank the many great friends—particularly Drs. Ligang Lyu, Dehua Mao, Guohua Hu, Yafei Wang, Ariane Middel, Bjoern Hagen, Qun Ma, Zhenxin Bian—who helped me in many ways such as sharing their data, providing financial supports, and/or introducing me to their networks and job opportunities. Also, I am too lucky to have the accompany of many gorgeous friends whose names I cannot detail here one by one. The episode Bones, in addition to William Clark’s analogy of sustainability science to health sciences and Elinor Ostrom’s diagnostic studies of common pool resources, has inspired me to delve into the problem-driven, diagnostic approach to advancing (landscape) sustainability.

I am very grateful for the financial supports from the School of Sustainability, the National Science Foundation (DEB-1342751, DEB-1342757), the Neely Foundation, the National Natural Science Foundation of China (41801169), the MOE (Ministry of Education in China) Project of Humanities and Social Sciences (18YJCH120), the US-IALE, and the Landscape Sustainability Science Forum.

Last and the most importantly, I am eternally grateful to my family for always having me back, unconditionally!
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES .................................................................................................................. x</td>
</tr>
<tr>
<td>LIST OF FIGURES .................................................................................................................. xi</td>
</tr>
<tr>
<td>CHAPTER</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1.1 Problem Context ............................................................................................................. 1</td>
</tr>
<tr>
<td>1.2 Problem Statement ......................................................................................................... 4</td>
</tr>
<tr>
<td>1.3 The Scope and Objectives .............................................................................................. 7</td>
</tr>
<tr>
<td>1.4 Overview of the Dissertation ......................................................................................... 14</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>2.1 Introduction .................................................................................................................. 20</td>
</tr>
<tr>
<td>2.2 Materials and Methods ................................................................................................. 21</td>
</tr>
<tr>
<td>2.3 Results .......................................................................................................................... 23</td>
</tr>
<tr>
<td>2.3.1 Public and Scholarly Interests .................................................................................... 23</td>
</tr>
<tr>
<td>2.3.2 Research Themes and Evolving Topics ..................................................................... 25</td>
</tr>
<tr>
<td>2.3.3 Intellectual Development Paths ................................................................................. 27</td>
</tr>
<tr>
<td>2.3.4 Contributing Scholars ............................................................................................... 29</td>
</tr>
<tr>
<td>2.3.5 Country Participation ............................................................................................... 31</td>
</tr>
<tr>
<td>2.4 Discussion ..................................................................................................................... 32</td>
</tr>
<tr>
<td>2.5 Conclusion .................................................................................................................... 39</td>
</tr>
</tbody>
</table>
3 RESEARCH PROGRESS AND KNOWLEDGE GAPS OF LANDSCAPE SUSTAINABILITY SCIENCE: A MULTIMETHOD BIBLIOMETRIC REVIEW

3.1 Introduction

3.2 Materials and Methods

3.2.1 Literature Search and Data Processing

3.2.2 Trend and Changepoint Detection

3.2.3 Text and Topic Mining

3.2.4 Citation Analysis

3.3 Results

3.3.1 Rapidly Growing Interest in Sustainability Studies of Landscapes

3.3.2 Multi-Facet Research Topics and Themes

3.3.3 Evolution Toward an Increasingly Transdisciplinary Research Field

3.4 Discussion

3.4.1 Progress and Challenges: Where Are We Now?

3.4.2 Perspectives from Sustainability Science for Moving Forward

3.5 Conclusion

4 URBANIZATION-ASSOCIATED FARMLAND LOSS IN CORE AND PERIPHERY AREAS: A MACRO-MICRO COMPARATIVE STUDY IN CHINA

4.1 Introduction

4.2 Analytical Framework and Diagnostic Hypotheses
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3 Materials and Methods</td>
<td>78</td>
</tr>
<tr>
<td>4.3.1. Land Use/Cover Data for Diagnosis of UAFL Patterns</td>
<td>78</td>
</tr>
<tr>
<td>4.3.2. Field Survey for Diagnosis of UAFL Causes and Consequences</td>
<td>80</td>
</tr>
<tr>
<td>4.4 Results</td>
<td>82</td>
</tr>
<tr>
<td>4.4.1. Farmland Loss Patterns in Core and Periphery areas of China</td>
<td>82</td>
</tr>
<tr>
<td>4.4.2. Farmland Loss Causes and Consequences in Frontier and Periphery of Urbanization</td>
<td>84</td>
</tr>
<tr>
<td>4.5 Discussion</td>
<td>89</td>
</tr>
<tr>
<td>4.6 Conclusion</td>
<td>93</td>
</tr>
<tr>
<td>5 UNDERSTANDING TEMPORAL FEATURES OF FARMLAND LOSS IN DRASTICALLY URBANIZING CORE-PERIPHERY SYSTEM: A LANDSCAPE SUSTAINABILITY PERSPECTIVE</td>
<td>95</td>
</tr>
<tr>
<td>5.1 Introduction</td>
<td>96</td>
</tr>
<tr>
<td>5.2 Materials and Methods</td>
<td>99</td>
</tr>
<tr>
<td>5.2.1. Study Area</td>
<td>99</td>
</tr>
<tr>
<td>5.2.2. Land Use/Cover Change and Landscape Pattern Analyses</td>
<td>101</td>
</tr>
<tr>
<td>5.2.3. Socioeconomic and Agrifood Dynamics Analyses</td>
<td>103</td>
</tr>
<tr>
<td>5.3 Results</td>
<td>105</td>
</tr>
<tr>
<td>5.3.1. Farmland Loss in Changing Core-periphery Landscape</td>
<td>105</td>
</tr>
<tr>
<td>5.3.2. Socioeconomic and Agrifood Dynamics</td>
<td>110</td>
</tr>
<tr>
<td>5.4 Discussion</td>
<td>113</td>
</tr>
<tr>
<td>5.4.1. Temporal Trends of Farmland Loss During Drastic Urbanization</td>
<td>113</td>
</tr>
<tr>
<td>CHAPTER</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5.4.2. Temporal Abnormalities of Farmland Loss and Why</td>
<td>116</td>
</tr>
<tr>
<td>5.4.3. Policy Implications and next Research Steps</td>
<td>119</td>
</tr>
<tr>
<td>5.5 Conclusion</td>
<td>122</td>
</tr>
<tr>
<td>6 CONCLUSION AND OUTLOOK</td>
<td>124</td>
</tr>
<tr>
<td>6.1 Summary of Major Findings</td>
<td>124</td>
</tr>
<tr>
<td>6.2 Significance of Research</td>
<td>128</td>
</tr>
<tr>
<td>6.3 Limitations and Future Directions</td>
<td>129</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>132</td>
</tr>
<tr>
<td>APPENDIX</td>
<td></td>
</tr>
<tr>
<td>A SUPPLEMENTARY INFORMATION, CHAPTER 2</td>
<td>155</td>
</tr>
<tr>
<td>B SUPPLEMENTARY INFORMATION, CHAPTERS 4&amp;5</td>
<td>160</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Overview of the Sampled Papers on Sustainability Studies of Landscapes</td>
<td>46</td>
</tr>
<tr>
<td>2. Most-Cited Publications by the Papers Sampled via Searching “Sustainable Landscape*” and “Landscape Sustainability”, Respectively</td>
<td>52</td>
</tr>
<tr>
<td>3. Characteristics of the Two Sampled Villages: Peri-Urban Versus Rural</td>
<td>85</td>
</tr>
<tr>
<td>4. Characteristics and Farmland Use of the Peri-Urban and Rural Households</td>
<td>86</td>
</tr>
<tr>
<td>5. Factors Influencing the Grain-Production Decision of the Peri-Urban and Rural Households</td>
<td>87</td>
</tr>
<tr>
<td>6. Grain Self-Sufficiency, Migration/Farming Tendency, and Life-Satisfaction of the Peri-Urban and Rural Households</td>
<td>88</td>
</tr>
<tr>
<td>7. Landscape Metrics for Quantifying Farmland Pattern and Hypothesized Changes During Urbanization</td>
<td>102</td>
</tr>
<tr>
<td>8. Development Stages by GDP per Capita and Associated Changes</td>
<td>104</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>The Three General Approaches to Advancing Sustainability</td>
</tr>
<tr>
<td>2.</td>
<td>Logical Structure of the Dissertation</td>
</tr>
<tr>
<td>3.</td>
<td>Different Trends of Interests in Sustainable Development, Sustainability Science, or Both</td>
</tr>
<tr>
<td>4.</td>
<td>Related but Different Research Themes and Evolving Topics of the Sampled Sustainable Development and Sustainability Science Articles</td>
</tr>
<tr>
<td>5.</td>
<td>Related but Different Intellectual Development Paths of the Sampled Sustainable Development and Sustainability Science Articles</td>
</tr>
<tr>
<td>6.</td>
<td>Related but Different Knowledge Bases: Co-Cited Scholars by the Sampled Sustainable Development and Sustainability Science Articles</td>
</tr>
<tr>
<td>7.</td>
<td>Related but Different Country Performances in the Sampled Sustainable Development and Sustainability Science Articles</td>
</tr>
<tr>
<td>8.</td>
<td>The Number of Papers With “Sustainable Landscape(s)” or “Landscape Sustainability” in Their Titles, Abstracts, and Keywords, and the Number of Citations to the Papers of Each Category</td>
</tr>
<tr>
<td>9.</td>
<td>Wordclouds of the Topics Identified From the Titles, Abstracts, Author’s Keywords, and ISI Keywords Plus of the Two Subsets of Papers That Were Sampled by Searching “Sustainable Landscape(s)” or “Landscape Sustainability”, Respectively</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>10. Clustering of the Topics Identified From the Author’s Keywords of the Two Subsets of Papers That Were Sampled by Searching “Sustainable Landscape(s)” or “Landscape Sustainability”, Respectively</td>
<td>50</td>
</tr>
<tr>
<td>11. Clustering of the Topics Identified From the Titles and Abstracts of the Two Subsets of Papers: “Sustainable Landscape(s)” and “Landscape Sustainability”, Respectively</td>
<td>51</td>
</tr>
<tr>
<td>12. Literature Development Paths of All the 333 Collected Papers on Sustainability Studies of Landscapes</td>
<td>56</td>
</tr>
<tr>
<td>14. Study Areas</td>
<td>80</td>
</tr>
<tr>
<td>15. Structural Dynamics of Farmland Loss to Other Land Uses in 2000–2015</td>
<td>83</td>
</tr>
<tr>
<td>16. Location and Elevation of Study Area</td>
<td>100</td>
</tr>
<tr>
<td>17. Farmland Transition in the Core-Periphery System</td>
<td>107</td>
</tr>
<tr>
<td>20. Land Use/Cover Conversion Flows During Study Periods</td>
<td>110</td>
</tr>
<tr>
<td>22. Agrifood Dynamics of the Core-Periphery System During 2000–2015</td>
<td>113</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Problem Context

Sustainability is the theme of our time, when many challenges such as population climax, climate change, environmental degradation, and social injustice will become acute (National Research Council 1999). However, the pursuit of sustainability is neither water without a source nor a tree without roots (Lélé 1991, Kidd 1992, Mebratu 1998). Since as early as three generations ago, some of the sustainability challenges such as environmental pollution and population explosion had raised local to regional awareness (Carson 1962, Meadows et al. 1972). Two generations ago, sustainability started to gain global momentum from both the North and the South, with the landmark Brundtland Report establishing the conceptual foundation of sustainability to unite the multidisciplinary scientific efforts (WCED 1987). With another generation’s interdisciplinary efforts, some streams of the sustainability studies seemed to be converging in the 1990s, featured by critical reflections on science and technology (Funtowicz Silvio and Ravetz Jerome 1984, Perrow 1984, Waldrop 1993), integrative long-term studies of the earth system (Turner II et al. 1990), increasing understandings of collective action for sustainability (Ostrom 1990), growing recognition of the need to transition to envisioned sustainable future (Meadows et al. 1992), and crying calls for building a new science enterprise to produce actionable knowledge (Funtowicz and Ravetz 1993, Argyris 1996, Stokes 1997). In this decades-long historical context, a novel field started to emerge at the turn of the twenty-first century, which we now know as

During the last two decades, sustainability science has been continuously evolving and rapidly expanding, with elevated numbers of publications and professional journals (Fang et al. 2018) as well as devoted institutions and educational programs (https://en.wikipedia.org/wiki/Sustainability_science). Reviews (Kajikawa et al. 2007, Kajikawa 2008, Jerneck et al. 2011, Spangenberg 2011) have implied growing consensus among scholars regarding sustainability science’s core concepts, key research themes, and foundational theories (Kates et al. 2005, Levin and Clark 2010, Bousquet et al. 2015, Fang et al. 2018, Clark and Harley 2019). A brand-new generation of scholars is in its formation that is by training committed to the science and practice of sustainability (albeit still with training challenges) (Killion et al. 2018). Most notably, early sparkling ideas—many of which were incorporated in the landmark NRC report (National Research Council 1999)—have resurged/developed into blossoming research fields, such as sustainability transitions research (Markard et al. 2012), transdisciplinarity research (Lang et al. 2012), urban sustainability research (Seto et al. 2012), land system science (Turner II et al. 2007), and landscape sustainability science (LSS) (Wu 2013b).

In the NRC report, land/landscape enters sustainability research discourses in mainly four different ways (National Research Council 1999). The first is about the long-term trends of land system change, including the increasing intensification of agriculture as well as the clearing of tropical forests and regrowing temperate zone forests. The second is about land-related sustainability challenges, such as land change related water
contamination, unintended effects of misusing land on ecosystems functioning, increasing pressure on land due to biofuels expansion, and land degradation in marginal or fragile areas. The third discourse treats land/landscape as a proxy for ecosystems as in wetland, coastal land, and grassland, or proxy for regions as in the case of the US landscape. The fourth talks about landscape as a concept of scale which is often referred to as the “landscape or regional scale.” These much reflect the main problem entries to address sustainability by mostly geographers from the land use/land cover research community, i.e., land system scientists (Turner II et al. 1995, IGBP Secretariat 2005, Verburg et al. 2015).

Compared to the relatively established land system science that has an active global network, clear research agenda, and professional journals, LSS – hereafter used as a convenient label for all landscape-relevant sustainability studies – is an infant research field advocated by some landscape ecologists (Naveh 2007, Wu 2013b), with mainly three problem entries to address sustainability (Benson and Roe 2000, Wu 2006, 2008, Pearson and McAlpine 2010, Turner 2010, Dramstad and Fjellstad 2011, Wu 2012, Levin 2015, Opdam et al. 2018). These include: (1) the transdisciplinary tradition long practiced within the landscape profession; (2) the spatially explicit approach with landscape pattern as a core focus; and (3) the multi-scale perspective that casts landscape as a “pivotal” scale to bridge local and global sustainability. As a matter of fact, these strands of efforts to help enhance sustainability could date back to the late 1980s (Thayer 1989, Forman 1990). In the last two decades, sustainable landscapes and landscape sustainability have become popular concepts in the studies of landscape ecology (Wu and
Hobbs 2002, Wu 2013a, 2017). More recently, some interdisciplinary scholars started to address the “parallel trajectories and increasing integration of landscape ecology and land system science” in contributing to sustainability (Roy Chowdhury and Turner II 2019), with efforts being made to proactively integrate the two (Vadjunec et al. 2018, Wu 2019). As an emerging research field, LSS seems to be of great potential to further develop into a bridge science that can integrate the multiple fields that address sustainability with various land/landscape-based problem entries (Antrop 2013).

1.2 Problem Statement

Yet, on the one hand, the development of LSS has gained momentum in the recent years in especially China, as catalyzed by the annual Landscape Sustainability Science Forum since 2013 (http://chess.bnu.edu.cn/FLSS/index.html) with growing numbers of attendees; on the other hand, compelling doubts on the emerging field of LSS have been raised by well-reputed scholars. For example, Benson and Roe (2000) posed a critical question by some of the landscape professionals—since the landscape profession had been practicing sustainability all along, what is more to be said by “sustainable landscapes”? More straightforwardly, Antrop (2006) proposed that “[a]s landscapes change continuously in a more or less chaotic way, the concept of sustainable landscapes could be viewed as a utopian goal.” Selman (2008) identified two broad “schools” in sustainable landscape development—“one focused on the design and protection of scenic assets and the other emphasizing dynamic multifunctional links between ecosystem services and human well being”—and he highlighted that “the idea of a ‘sustainable landscape’ often remains undefined, or is defined in relation to specific applications and
geographical contexts.” Alternatively, Wiens (2013) suggested two ways to view landscape sustainability—one implies “the degree to which the patterns and processes that characterize a landscape will persist indefinitely into the future” and the other connotes actually the sustainability of ecosystem services delivered by the landscape—and he argued that both conceptions are useless in a changing world in which “[a] conventional view of sustainability no longer seems relevant to landscapes.” In the seminal paper where LSS was proposed, Wu (2013b) summarized existing definitions/descriptions of sustainable landscapes and landscape sustainability, and responded to the doubts with Forman’s adaptability-based argument for sustainable landscapes (Forman 1995). Over the past few years, the awareness and efforts to build stronger theoretical and methodological foundations have been accumulating (Musacchio 2009b, a, Termorshuizen and Opdam 2009, Cumming 2011, Wu 2013b, Luc 2015, Gibbons et al. 2018, Liao et al. 2020). Nonetheless, the scientific foundations of the so-called LSS remains poorly communicated.

For practical applications of LSS, on the one hand, empirical studies archived in Scopus that claim relevance to LSS have been rapidly increasing; on the other hand, however, archetypical examples remain limited that can showcase what LSS has to offer landscape practitioners. Liao et al. (2020) highlighted two practical examples of LSS: One on sustainable intensification of agricultural landscapes and the other on land sharing versus land sparing to reconcile agricultural production and biodiversity conservation. Yet, the two examples, as have been long studied in land system science, are highly context-dependent and not of broad generalizability. That said, some case studies do
show methodological generalizability to potentially serve as archetypical examples of LSS. For instance, Bray and colleagues reported on the relatively stable forest cover in Mexico in contrast to the commonly documented tropical deforestation and reforestation, and deciphered how community forest enterprises were able to sustain the forest with the common property regime (Bray et al. 2003, Bray et al. 2004). Saura and his colleagues developed a systematic methodology based on landscape connectivity for prioritizing habitat conservation (Saura and Torné 2009, Bodin and Saura 2010, García-Feced et al. 2011, Gurrutxaga et al. 2011), which can be further extended to engage stakeholders (Opdam et al. 2006). Liu et al. (2020) demonstrated a simulation-based methodology to assess how alternative urban development patterns affect landscape sustainability that considers water scarcity, food security, habitat conservation, and flood risk. Nonetheless, these empirical studies’ scientific relevance to and theoretical significance for LSS remain to be addressed.

The unclear scientific foundations of LSS and the paucity of archetypical empirical studies can be very problematic. In the first few years of studying LSS, I frequently found myself at a hard time in classrooms, conferences, and talks with my non-academia friends when I tried to explain what my research area is or what LSS is really about. The most frustrating experience was when the founding father of the North American school of Landscape Ecology and also one of the first pioneers in studying sustainable landscapes, Dr. Richard Forman, visited our lab on March 30, 2016. During the self-introduction session, we each briefly talked about our research areas and I said LSS with sincere eagerness to know what this great scientist thinks about the research directions of
LSS. Sadly, Dr. Forman seemed quite unsatisfied with my articulation of what landscape sustainability means, and he also seemed to disagree with others’ interpretation of his studies of ecologically sustainable landscapes (please note that this is not endorsed by Dr. Forman but rather my personal impression). It was then that I realized the problem that the science of landscape sustainability is not crystal to others and remains to be better understood. Equally frustrating was my experience of the last few years of studying LSS, when I have been very struggling in finding support to fund my research. My family and friends in the non-academia asked about what my research field can actually contribute in the real world, while friends in the traditional disciplines often asked for concrete empirical studies to show anything new that my research field can offer. It was then that I realized from time to time the problem that the practical value of landscape sustainability research has not been well communicated.

Addressing the two interlinked problems of LSS – the unclear scientific foundations and the paucity of archetypical empirical studies – is a critical and urgent task for sustaining and advancing this over three-decade old infant field. Poor communication of what the ‘science’ is in LSS and what LSS has to offer to sustainability practices in the real world has consequences, e.g., underappreciation of LSS by sustainability researchers and practitioners, losing attraction to next generations of landscape scholars, and likely, leaving a false impression on LSS as a club game of merely publishing fancy papers.

1.3 The Scope and Objectives

By this dissertation, I hope to help scholars outside the field and the non-academia to get a better sense of LSS. The aim is to address the above-mentioned two grand
problems (i.e., the unclear scientific foundations of LSS and relatedly, the paucity of archetypical empirical studies) within a manageable scope. To this end, this dissertation will cover two parts: revealing the scientific foundations of LSS and providing empirical examples of some well-recognized concrete landscape-relevant sustainability issue.

It is not my intention to claim to ‘provide’ scientific foundations to LSS. As said earlier, this field has been over three decades old, and there do exist expert-based delineations on the theoretical foundations of LSS, such as sustainability science in general, landscape ecology in general, resilience theory, and hierarchy theory and cross-scale interactions (Wu 2013b, Liao et al. 2020). In this dissertation, I intend to supplement the existing efforts by depicting a more objective, evidence-based picture of LSS’s existing scientific foundations, from specifically two perspectives.

One is the sustainability science perspective. An interesting observation is that, though LSS has been claimed to be a necessary constituent science of sustainability science or the sustainability research enterprise, the “science” of sustainability science itself is still open to question. The emergence of sustainability science started merely two decades ago, while landscape scholars’ sustainability studies of landscapes could date back to the late 1980s when the sustainable development movement gained global momentum. There is a good risk that what has been believed to be sustainability science in the LSS literature turns out to be something different or obsolete. The potential miscommunication of sustainability science might well hinder the development of LSS and even stigmatize sustainability science itself. Therefore, as the first and foremost step
of this dissertation, I will analyze whether and how sustainability science differs from the conventional sustainable development research, based on objective evidence.

The other is a historical perspective. This is based on another interesting observation that, even after more than three decades of research relevant to LSS, there is yet no review of the field. Worse still, the core concepts of LSS, sustainable landscapes and landscape sustainability among others, remain controversially understood. Science and meaningful scientific discourses are built on clearly defined concepts (Wu and Hobbs 2007). Moreover, the lack of a historical review of relevant studies could result in a high risk that the diversity of perspectives on LSS is underrecognized, with insightful yet maybe very biased ideas advocated as the scientific foundations of LSS. Therefore, as the second step of this dissertation, I will systematically review the past and now of LSS based on objective evidence as much as I can, and further, discuss the research gaps for moving LSS forward.

Likewise, for the empirical part of the dissertation, it is not my intention to claim to provide the right or best example of LSS applications. Rather, based on the found knowledge gaps in LSS (to be discussed in Chapter 3), I intend to provide one example of the problem-driven, diagnostic landscape sustainability research. Broadly speaking, as per John Wilson’s trichotomy of the structural elements of ideology for frame resonance and participant mobilization (Wilson 1973, Snow and Benford 1988), there are three
interconnected methodological approaches to advancing (landscape) sustainability (Fig. 1.1): diagnostic, prognostic, versus transformational\(^1,2\).

![Diagram of sustainability approaches]

**Figure 1.1** The three general approaches to advancing sustainability—diagnostic, prognostic, and transformational—following Wilson (1973) and Snow and Benford (1988), with the figure adapted from the Eight-Theme Framework of Sustainability Science by Fang et al. (2018).

First is the problem-driven, diagnostic approach, which is retrospective starting with the diagnosis of the undesirable status quo (Fig. 1.1, from \(T_0 + t_2 + t_3\) to \(T_0 + t_2\) and to \(T_0\)). It is like seeing a doctor who heals “sustainability diseases,” and usually involves two tasks: (1) problem identification—building consensus on what the problem is; and (2) causal attribution—building consensus on what caused the identified problem. One may quickly think of the Ostromian studies (Anderies et al. 2004, Ostrom 2007, Ostrom 2009, Ostrom 2011).

---

\(^1\) Wilson (1973) developed the trichotomy of the structural elements of ideology: diagnosis (how things got to be how they are), prognosis (which should be done and what the consequences will be), and rationale (who should do it and why). Later, Snow and Benford (1988) adopted this trichotomy for decomposing the three core tasks of framing: diagnostic framing, prognostic framing, and motivational framing. In this dissertation, I rename “motivational” as “transformational” in the context of the sustainability literature, e.g., Wiek and Lang (2016) and Markard et al. (2012).

\(^2\) This part will be further developed into a manuscript for submission as a perspective paper.
and Cox 2010, Poteete et al. 2010) as examples of this diagnostic sustainability research, in which the focal problem is common pool resource or collective action dilemma with a structured pool of candidate causes to examine. Moreover, there is another subtype of this diagnostic sustainability research (WBGU – German Advisory Council on Global Change 1997, Schellnhuber et al. 2002, Lüdeke et al. 2004, Srinivasan et al. 2012), in which the problem is not as clear as in the Ostromian studies and has to be identified at the first place before making any causal attribution. For example, Stellmes et al. (2013) integrated remote sensing imagery, demographic and climatic data, and mapped out six syndromes of global land-cover transformations. Yet, the Ostromian style diagnostic research in LSS is still rarely seen.

Second is the solution-oriented, prognostic approach, which is prospective starting with the prognosis of tentative sustainability prescriptions (Fig. 1.1, from $T_0$ to $T_0+t_2$ and to $T_0+t_2+t_3$). It is like working with a regimen instructor who advises not to take drugs, and usually involves also two tasks: (1) solution prescriptions – developing candidate strategies, tactics, and policies that target some identified problem(s); and (2) solution prognoses – selecting the best possible solution from the candidates based on the sustainability trade-offs between intended and unintended effects of the proposed solutions. One may quickly think of the IPCC studies (Edenhofer et al. 2015) as examples of this prognostic sustainability research, in which the multidimensional socio-environmental sustainability outcomes of preset sets of scenarios are compared. For such an example in LSS, I again refer to Liu et al. (2020). By focusing on a set of identified landscape sustainability challenges (i.e., water scarcity, food security, habitat
conservation, and flood risk), they compare the simulated outcomes of the business-as-
usual scenario and a preset urban development scenario, and conclude that the proposed
intervention is a sustainable plan. Currently, making solution prognosis via usually
scenario-based simulations is popular in this prognostic sustainability research, yet the
process of brainstorming based on diagnostic findings to prescribe possible solutions is
still in urgent need of much more science.

Third is the use-inspired, transformational approach, which is retrospective starting
with the envisioning of a desirable future (Fig. 1.1, from $T_0+t_2+t_3$ to $T_0+t_2$ and to $T_0$). It
is like working with a fitness instructor who guides in building good shapes, and involves
usually three core tasks: (1) envisioning desirable future – building consensus on what
sustainable future we want; (2) identifying future-reality gaps – building consensus on
collective action priorities; and (3) mobilizing transformational actions – motivating
stakeholders to take the needed actions. This transformational style sustainability
research is echoed by Amartya Sen’s “informed agitation” as so advocated by William
Clark and his colleagues (Clark et al. 2016, Clark and Harley 2019). With a long legacy
from Meadows et al. (1992), Meadows (1997), it has developed into probably the most
blossoming subfield of sustainability science (Wiek et al. 2012, Wiek and Lang 2016,
the transformational methodology for studying sustainability and (Wiek et al. 2012)
compile a rich number of case studies. Such an approach is probably also the most
popular in LSS under the name of design-thinking or a design perspective, often featured
by the emphasis on stakeholder engagement and participatory planning. Yet, though this
transformational approach has been gaining increasing traction from the policy world and the new generation of sustainability scholars (especially those with social science backgrounds), it risks the critique of lacking science due to the learn-by-doing action-first tendency instead of following the knowledge-first tradition.

The prognostic approach treats sustainability as more a process or property, asking “what if” questions; while the diagnostic/transformational approaches views sustainability as a more state or goal, asking “why/how” questions. The diagnostic approach focuses on understanding and improving a problematic today, the prognostic approach focuses on determining the best possible human interventions to take (e.g., sustainable resource management, sustainable landscaping), while the transformational approach focuses on whom to mobilize to do what and for why such that the collectively desired sustainable future can be made to happen. The three approaches all rely on better understandings of the human-environment systems and the knowledge-action gap.

However, in a complex and uncertain world (WBGU – German Advisory Council on Global Change 1997) with normative (Funtowicz and Ravetz 1993) and urgent (Lubchenco 1998) sustainability challenges, more studies need to take the problem-driven, diagnostic approach (Clark et al. 2016), which so far has been comparatively underused especially in the studies of LSS (see Chapter 3 for evidence).

In light of the three different methodological approaches to advancing (landscape) sustainability and in recognition of the need of more diagnostic sustainability research, I will focus the empirical part of this dissertation on the issue of farmland loss during rapid urbanization. The urbanization-associated farmland loss (UAFL) phenomenon has been
reported worldwide, and has raised regional to global concerns on the consequent food insufficiency (Edgens and Staley 1999, Seto et al. 2000, Bren d’Amour et al. 2017). Farmland preservationists typically frame the issue as a problem of food self-insufficiency due to urban encroachment of farmland, especially high-quality farmland (Tan et al. 2005, Jiang et al. 2012, Pandey and Seto 2015, Bren d’Amour et al. 2017, Liu et al. 2019). However, opponents strongly doubt if farmland loss would actually cause food insufficiency and whether urban development is responsible for farmland loss (Fischel 1982, Edgens and Staley 1999, Gottlieb 2015). To date, whether and how to protect farmland from urbanization has remained a decades-long policy debate among stakeholders such as farmers, the agri-food industry, urban developers, and land use managers (Fischel 1982, Edgens and Staley 1999, Azadi et al. 2012).

In this dissertation, I will address the UAFL issue in the context of China, where ensuring grain self-sufficiency is a national strategy and farmland preservation has been written into laws as a policy imperative. The objectives are: (1) to examine the validity of the popular problem framing and associated causal attribution of UAFL that urban expansion onto farmland threatens food security, or more specifically, grain self-sufficiency in the context of China; and if necessary, (2) to develop new problem framing and causal attribution of UAFL for more effectively mobilizing stakeholders to preserve farmland.

1.4 Overview of the Dissertation

This dissertation has six chapters: the introductory chapter, four research chapters, and the concluding chapter. The next four chapters are the research chapters, two on the
scientific foundations of LSS and the other two on the problem-driven, diagnostic research example of LSS. The final chapter summarizes the major findings of the research, elaborates on their scientific and practical significance to landscape sustainability, and discusses the main limitations of the dissertation as well as my future research steps. The logical structure of the whole dissertation is as follows (Figure 1.2):

**Figure 1.2** Logical structure of the dissertation.

The two empirical studies were built on the findings of the two conceptual studies, with the four research chapters together contributing to help link the science and practice.
of landscape sustainability through the still underused problem-driven, diagnostic approach. Specifically, the research questions or hypotheses addressed in each of the four research chapters and corresponding research designs are as follows:

Chapter 2: Distinguishing Sustainability Science from Conventional Sustainable Development Research

The null hypothesis is that sustainability science is nothing but “old wine in a new bottle”—essentially the same as sustainable development research—just with a different name. To test this hypothesis, I with help from collaborators have collected data from Google Trends, Google Books Ngram Viewer, and publications archived in Scopus for sustainability science and sustainable development research separately, and analyzed their consistency in terms of temporal trends of public and scholarly interests, research themes and evolving topics, intellectual development paths, main contributing scholars, and country participation/contribution.

Chapter 3: Research Progress and Knowledge Gaps of Landscape Sustainability Science: A Multi-Method Bibliometric Review

The research questions include: (1) Are the sustainability studies of landscapes coalescing and developing into a science? Specifically, has the number of such studies been increasing in terms of annual publications and citations? (2) What are their main research topics and themes, and how has their research focus evolved? (3) What are the main challenges and directions for developing an integrative landscape science that can help enhance sustainability? With help from collaborators, I have collected relevant publications from Web of Science—based on two core concepts, i.e., sustainable
landscape(s) and landscape sustainability—and addressed the research questions using multiple methods, including change-point detection, text and topic mining, and citation analysis.

Chapter 4: Urbanization-Associated Farmland Loss in Core and Periphery Areas: A Macro-Micro Comparative Study in China

In this chapter, I focus on the causal attribution part of a problem-driven, diagnostic study, by reexamining three popular beliefs/hypotheses regarding the UAFL issue: (1) urban expansion is responsible for farmland loss; (2) farmland loss is responsible for decreasing grain production; and (3) decreasing grain production instead of increasing grain demand is responsible for grain self-insufficiency, if any. To test these hypotheses, I with help from collaborators have collected remote sensing-based land use/cover data of China in 2000, 2005, 2010, and 2015, as well as rural household survey data in two case study villages of China with one rural the other peri-urban. We have analyzed the different proportions of farmland loss to other land use/cover types during 2000-2015 in the core and periphery areas of China, and compared the influencing factors of farmers’ decision-making in grain production and grain production and consumption of rural households in the two villages—the frontier and periphery of urbanization.

Chapter 5: Understanding Temporal Features of Farmland Loss in Drastically Urbanizing Core-Periphery System: A Landscape Sustainability Perspective

In this chapter, I focus on the problem identification part of a problem-driven, diagnostic study, by proposing and addressing three questions regarding the UAFL issue from a landscape sustainability perspective. The research questions include: (1) What are
the landscape features of UAFL and how do the features change over time? (2) What are the underlying human-environment interactions that give rise to these features? (3) What are the implications of these human-environment interactions for sustainability? With help from previous collaborators, I have collected relevant data for a drastically urbanizing core-periphery system in China, including remote sensing-based land use/cover data in 2000, 2005, 2010, and 2015, as well as data on socioeconomic and agrifood dynamics. I have addressed/discussed the questions based on geospatial analysis, landscape metrics-based analysis, land use conversion matrix analysis, and changepoint detection.
CHAPTER 2
DISTINGUISHING SUSTAINABILITY SCIENCE FROM CONVENTIONAL SUSTAINABLE DEVELOPMENT RESEARCH

Abstract

Sustainability science (SS) is the science of and for sustainable development (SD). Does the research historically identified as SD, however, fit within the framing of SS? Is SS a new or reformulated vision of SD? Here we present a comparative bibliometric analysis of 1,063 SS and 1,063 top-cited SD publications collected from Scopus to address these questions. With the addition of Google Trends and Google Books Ngram Viewer data, we identify the trends of public and scholarly interests, the temporal development of literature, knowledge bases, and country performances associated with SD and SS publications. We found: (1) SS reformulates SD as part of the social-environmental system, whereas the conventional SD research focuses on various sectoral issues. (2) SS is increasingly moving from integrative science assessment to transdisciplinary science-action, while SD research at large has moved from a global change to a business-industrial emphasis. (3) SD has been losing public interests since 2004 until 2015 when Sustainable Development Goals were launched, while SS has received rapidly growing interests from 2006 onward. Our findings suggest that, though by no means ‘old wine in a new bottle’ and rapidly expanding, SS is still notably marginal in the SD research landscape, and that, to refuel the global SD movement, further integration of conventional SD research with SS is urgently needed.
2.1 Introduction

After two decades of development in the academic literature (National Research Council 1999), sustainability science (SS) is arguably coming of age (Fang et al. 2018, Sala et al. 2019), commanding “a room of its own” (p. 1737) (Clark and Dickson 2003). As a human-environmental science (Kates et al. 2001, Clark 2007, Kates 2011b), its identity involves various configurations of the following elements: (i) meeting the needs of humanity, (ii) reducing hunger and poverty more equitably, (iii) without threatening Earth’s life support systems (National Research Council 1999, Kates et al. 2001). The initial framers of SS in the United States (National Research Council 1999), called for a framework of sustainable development (SD), with subsequent characterizations of SS as informing or addressing SD (Clark 2007, Matson et al. 2016). Such links between SS and SD were further strengthened by such initiatives as the United Nations Sustainable Development Goals that expand the needs of humanity beyond hunger and poverty and include sustaining Earth’s life support systems (United Nations 2015).

To many of its practitioners, SS is beyond doubt “…something different…in the air…. that is intellectually exciting, practically compelling….“ (p. 8060) (Clark and Dickson 2003). As originally outlined (National Research Council 1999), SS focuses on generating place-based understandings of human-environment interactions and linking knowledge with action to inform a sustainability transition (Kates et al. 2001, Clark and Dickson 2003, Kates and Parris 2003, Turner II et al. 2003, Kates et al. 2005, Clark 2007, Kates et al. 2011b).

---

3 This chapter benefited from collaboration with Billie L. Turner II, Dehua Mao, Jianguo Wu, Marco Janssen, John M. Anderies, and Rimjhim Aggarwal, and will be submitted for publication after final revisions.
Ostrom 2007, Levin and Clark 2010, Kates 2011b), characteristics subsequently applied in 43 identities and 70 core research questions of SS (Fang et al. 2018). Others, including practitioners from within and beyond SS, seem to equate SS and SD research at large (Kajikawa et al. 2007, Bettencourt and Kaur 2011, Kajikawa et al. 2014, Elsevier 2015). After all, SD has historically addressed people and resources in place, with strong ties to application for improving human well-being.

Is SS a relabeling or reuse of the SD arena, or is it something new? Those engaging SD and SS research respond to these queries variably. Systematic assessments of SS have rarely been attempted, however. Such assessments should provide insights about the similarities and distinctiveness between SD and SS studies. To identify the characteristics in question, we provide such an assessment by contrasting the temporal trends of SD and SS as captured by Google Trends (number of internet searches using Google), Google Books (archived by Google), and scholarly publications (searched in Scopus with <“sustainable development”> or <“sustainability science”> as the topic query), and further, by multidimensional content-based comparisons of SD and SS publications using multiple bibliometric tools (VOSviewer, HistCite™, and Bibliometrix R package). Our results flesh out the identity of SS as the “use-inspired basic research” strand of SD studies (p. 1737) (Clark 2007), and moreover, highlight three contemporary challenges for SS to better serve the pursuit of SD.

2.2 Materials and Methods

We conducted a literature search on March 14th, 2019, using the Scopus database (www.scopus.com) to sample peer-reviewed papers in the SD and SS categories. As
sustainability is inter- and trans-disciplinary, the range of journals reviewed by Scopus is more suitable than that by the Web of Science. By searching <“sustainable development”> in the titles, abstracts, or keywords of the papers published in English, 159,394 SD documents were identified. Similarly, the search of <“sustainability science”> generated 1,063 SS documents. To maintain consistency in the results, the top 1,063 cited SD documents were included in the analyses (Fig. S2.1 schematic diagram of the paper sampling). This approach yielded different time periods in which the sampled papers appeared: 1987-2017 and 2001-19 for SD and SS, respectively (Appendix A, Table S2.1 overview). Bibliographic information on SS and top-cited SD documents were saved separately for the comparative analyses, including text and topic mining, historiographic mapping, and co-citation analysis. Details of the analysis methods and tools can be found in ref. (Zhou et al. 2019). The seminal publications identified in historiographic mapping (Table S2.2 details) were reviewed by full-text to help examine how research has evolved. In addition, Google Trends (trends.google.com) were used to compare the relative search volumes of the queries <“sustainable development”> and <“sustainability science”> via the Google search engine (Choi and Varian 2012), and Google Books Ngram Viewer (books.google.com/ngrams) were used to compare the relative occurrence frequencies of the phrases <“sustainable development”> and <“sustainability science”> in the text corpus of 5,195,769 digitized books containing ~4% of all books ever published (Michel et al. 2011). Besides, Spearman correlation coefficients were calculated in R to detect the relationships of the SS and SD in terms of their temporal trends of publication number.
2.3 Results

2.3.1 Public and Scholarly Interests

Our results from Google Trends, a tool used for tracking temporal change in public search interest of any term, show that during the last fifteen years worldwide interests in SD have been decreasing, but those in SS have been increasing since 2006 (Fig. 2.1A). At least two observations affect interpretations of these trends, however. First, contemporary SD entries maintain about 40 times the entries to that of SS, given its multiple decades’ longer topical attention compared to SS. Second, both SD and SS search interests have risen since the United Nations announced its Sustainable Development Goals in 2015 (Fig. 2.1A).
Figure 2.1 Different trends of interests in sustainable development, sustainability science, or both as searched using the two labels. (A) Worldwide Google search interest from 01/01/2004 to 12/31/2018 (thin lines – monthly trends and bold lines – annual trends), data from Google Trends (https://trends.google.com/trends) and normalized by monthly maximum. (B) Normalized phrase frequency (one-year smoothing) in books predominantly in the English language published in any country from 1950 to 2008, data from Google Books Ngram Viewer (https://books.google.com/ngrams); sampling inspection shows that the short bump of sustainability science in the early 1990s before the term was formally established is actually “sustainability punctuation science”. (C) Number of documents published in English, data from Scopus (https://www.scopus.com); note that the left and right y-axes are of different magnitudes.

The Google Trends are consistent with the trends of the phrase frequency in Google books between 1950 and 2008, published predominantly in English (Fig. 2.1B). SD gained rapid attention beginning the late 1980s, before leveling off in the late 1990s and
declining since about 2005. By contrast, SS phase frequency in Google Books has skyrocketed from 2000, though its magnitude is at least two orders lower than that of SD because of the much shorter publication duration of SS.

A different picture emerges for the academic world as archived by Scopus (Fig. 2.1C). Scholarly interests in SD and SS have both been increasing, recognizing the higher magnitude of SD publications noted above. About one third of the SS papers mention SD in their titles, abstracts, or keywords. The temporal correlation between the two research domains is statistically significant ($p < 0.001$), with a Spearman correlation coefficient of 0.89. While the trend of the overlapping papers that mention SS and SD is statistically more correlated to that of SS than the SD literature (0.98 versus 0.88, with both $p < 0.001$). The magnitude contrast and temporal correlations indicate SS as a marginal yet rapidly expanding research domain in the SD literature, with growing idiosyncrasy.

2.3.2 Research Themes and Evolving Topics

The most relevant Author’s Keywords – occurring 10 or more times – show related but different thematic and temporal patterns for the SD studies and SS. The mapped 19 SD keywords fall into five thematic clusters: 1) vulnerability and adaptation studies in the context of climate change; 2) energy issues, especially renewable energy and biomass studies; 3) life cycle assessment and environment studies; 4) business-related sustainability studies, for example, supply chain management and corporate social responsibility; and 5) studies variously addressing ecosystem services, governance, and industrial ecology, especially in the context of China (Fig. 2.2A). The mapped 27 SS keywords also cluster into five research themes that are more tightly intra-connected than
those for SD: 1) vulnerability, adaptation, resilience, and development studies in the context of climate change; 2) inter- and trans-disciplinary studies of social-ecological systems, from the perspectives of ecosystem services, governance, land use and social learning; 3) inter- and trans-disciplinary studies by collaboration and stakeholder engagement; 4) education-related sustainability studies (e.g., higher education, ontology and methodology of SS); and 5) transformative SD (Fig. 2.2B). Compared to SD, SS has focused notably less on business-related topics (e.g., supply chain management and industrial ecology), but shared the topics of climate change, vulnerability, and adaptation. Importantly, SS has generated new research themes, the most prominent being the inter- and trans-disciplinary research on social-ecological systems, and sustainability theory and education. In contrast, SD research has moved from a global change to a business-industrial emphasis since about 2010 (Figs. 2.2C-D).

---

4 Social-ecological systems also refer to social-environmental and human-environmental systems. Here we use social-ecological systems to refer to a specific entity of research, in part because of its common usage for the phenomenon examined in the literature. Such systems undergird human-environmental science, of which sustainability science is part.
Figure 2.2 Related but different research themes and evolving topics of the sampled sustainable development (left) and sustainability science articles (right), generated by VOSviewer. See Table S1 for an overview of the sampled papers. Clustering of research topics (i.e., key themes): (A) vs. (B); temporal evolution of the research topics: (C) vs. (D). Topics were extracted from Author’s Keywords; \( N = 2690 \) for sustainable development, and \( N = 2693 \) for the sustainability science research. Mapped topics are restricted to those occurring 10 or more times, with their node sizes proportional to their relative occurrences; colors denote different groups identified by default settings.

2.3.3 Intellectual Development Paths

SS appears to have developed a more cohesive intellectual community than has SD, based on local citations (citations from the 1,063 sample in the analysis) among the top 25 papers in either of the two categories. This observation is illustrated by many scattered and largely disconnected thematic ‘islands’ in the SD literature and the highly
interconnected thematic papers for SS (Fig. 2.3). Also, the top 25 papers in SD, measured by local citations, range across journals representing many disciplines or research fields. In contrast, the complementary set of SS papers were largely published in *Sustainability Science* and *Proceedings of the National Academy of Sciences of the United States* (Appendix A, Table S2.2). Again, this distinction for SD may signal the emergence of small research networks and confluence of others about a decade ago (Fig. 2.3A, left and right parts). Full-text reading of the mapped SD papers suggests a bifurcated set of research linkages, one emphasizing social-technical innovations for sustainability transitions, and the other about supply chain management for sustainable business (Fig. 2.3A). Interestingly, three of the mapped SS papers (labeled in blue, Fig. 2.3B) are also included in the sampled SD papers, indicating modest relationships between of SS with SD studies. A full-text reading of the SS papers (Appendix A, Table S2.1) indicates that the seminal papers before 2007 addressed the conceptual and theoretical basis of SS following a social-ecological systems orientation, and that papers since 2012 have focused more so on action-oriented, transdisciplinary research.
Figure 2.3 Related but different intellectual development paths of the sampled sustainable development (A) and sustainability science articles (B), generated by HistCite. Mapped papers are restricted to those with local citations (i.e., times cited by sampled papers) ranking in the top 25. Arrows refer to citations. Node size is proportional to the number of local citations, yet incomparable between the left and right panels. The three papers in the right panel are also included in the sampled sustainable development articles. See Table S2 for the details of each seminal article.

2.3.4 Contributing Scholars

The most-cited scholars and their co-citation pattern provide clues to the knowledge bases of the sampled papers. These scholars in SD are loosely connected and rarely cited concurrently (Fig. 2.4A). In contrast, the most-cited scholars within the SS label cluster into three tightly intra-connected groups (Fig. 2.4B). The left group identifies researchers from the ecological community, especially linked to resilience research, and some human-environment researchers variously linked to former and extant international
research programs (e.g., IGBP, IHDP, DIVERSITAS, EcoServices, GLP). The right group identifies individuals engaged in transdisciplinary research dealing with actionable knowledge. The middle group may best be distinguished as cross-boundary scholars with long-term efforts in promoting SS, commonly adopting a sustainable development focus within SS and with strong attention to science informing application. Likewise, various SD researchers focus on sustainability transitions in which the knowledge base for SD and SS overlaps.

---

5 IGBP – International Geosphere-Biopshere Programme, IHDP – International Human Dimensions Programme; EcoServices and GLP (Global Land Programme) are part of Future Earth.
6 Transdisciplinary research is variously identified as post-normal science, mode 2 science, post-academic science, problem-oriented research, science in action, mandated science, triple helix, strategic research, and, in a few cases, sustainability education (Scarano 2019)
Figure 2.4 Related but different knowledge bases: Co-cited scholars by the sampled sustainable development (A) and sustainability science articles (B), generated by VOSviewer. Note that these scholars may not self-identify as sustainability scientist. Mapped scholars are restricted to those with at least 110 citations from the sampled articles (i.e., local citations). Node size is proportional to the number of local citations, yet incomparable between the two panels; colors denote different groups identified by default settings.

2.3.5 Country Participation

In terms of publication and citation numbers, the top ten countries in which SD and SS reside and publish are subtly different, although both are dominated by developed countries (Fig. 2.5). Based on the literature examined, the top-cited ten country sources for SD research accounted for more than 64% of the publications and 67% of the citations. That for SS research contributed 57% of the publications and more than 82% of the citations.
the citations. United States’ sources dominated the two measures for SD and SS, followed by other G7 countries. The United Kingdom, home to various major figures in SD, including the older SD focus (see Discussion) was the second source for and citations to SD research, whereas Germany, Japan, and Australia ranked within the top countries for SS. China has become a major source of SD research and increasingly SS as well. South Africa rises into the top ten in terms of SS citations, owing to several major researchers in that country engaged to sustainability research.

**Figure 2.5** Related but different country performances in the sampled sustainable development (upper) and sustainability science articles (lower). Top 10 most productive countries – (A) vs. (B) – with values on the right showing the total numbers of publications. Top 10 most cited countries – (C) vs. (D) – with values on right showing the total citation numbers.

**2.4 Discussion**

At least three major caveats have possible implications for our results and interpretations. First, only papers published in English were sampled in our analysis, muting, for example, the increasing attention to SS and SD literature in Chinese and
Japanese language journals (Fig. 2.5). This limitation is inherent in bibliometric reviews.

Second, we searched with only <“sustainable development”> or <“sustainability science”> as the topic query, creating an incomplete set of the SD and SS literatures, missing that directly relevant to the two labels but lacking the terms in titles, abstracts, and keywords. Including more phrases in the query is possible, but begs the issue of what topic queries to employ based on what standards. Third, only the top-cited 1,063 out of the 159,394 SD papers were analyzed (Fig. S1 schematic diagram of the paper sampling). Full inclusion of the SD papers is possible (as in ref. (Kajikawa et al. 2007)), but will lead to incomparability with the 1,063 SS papers.

Notwithstanding our including only the top-cited 1,063 SD papers, our findings are generalizable at the research domain level, as evidenced by the consistent findings in previous bibliometric analyses. Kajikawa and colleagues (Kajikawa et al. 2007) analyzed the full collection of papers sampled by searching the terms <“sustainability”> or <“sustainable”> in title, abstract, and keywords from Web of Science in 2006, updated in 2013 (Kajikawa et al. 2014). The resulting sustainability papers reflect mainly the SD research, as Bettencourt and Kaur (Bettencourt and Kaur 2011) examined the papers published before 2009 in Web of Science by searching separately <sustainability> and <sustainable development>, and concluded that the SD papers were a subset of the sustainability papers (accounting for about 80%), with very similar properties (confirmed by our experimental comparison shown in Fig. S2.2). Kajikawa and colleagues (Kajikawa et al. 2007, Kajikawa et al. 2014) found SS themes emerging in the disciplinary SD research landscape—they concluded that by 2006 sustainability was largely separated
among disciplinary interests, but by 2013 bridging research hubs had emerged focused on human-environment relationships, knowledge systems and transdisciplinarity, and transition management. Somewhat complementary, we found that SD studies are fragmented and dominated by business-related sectoral issues (Fig. 2.2A), with social-technical innovations for sustainability transition and supply chain management for sustainable business emerging around 2010 (Fig. 2.3A). In contrast, by 2007 SS maintained a cohesive research community with the social-ecological system research at its core, and with transdisciplinarity research as an increasingly prominent theme since 2012 (Figs. 2.2B and 2.3B).

Our assessment largely underrepresented the “older” SD literature in the late 1980s to 1990s. Some of the older SD literature did not use the SD label in the three identification roles applied in our assessment or has not been highly cited. 7 The older SD research centered on the development of impoverished communities in the Global South. Not consistent in the use of SD (Lélé 1991, Kidd 1992, Castro 2004), this literature focused mainly on rural communities’ primary production with the intent of improving livelihoods with minimal losses of the resources required for that production. Much of this literature drew on the definition of SD as articulated by the World Commission on Environment and Development (i.e., the Brundtland Report) (WCED 1987). The various studies undertaken, however, tended to examine localized human-environment relationships, emphasizing socioeconomic concepts and theories to interpret the

---

7 Note as well that our query-based paper sampling method also affected the SS literature examined. Land system science (Turner II et al. 2007), for instance, plays a major role in sustainability programs and in the published literature, but much of it fails to use SS in one of the three identification roles.
sustainable use of resources and advance possible solutions (e.g., refs. (Clark 1973), (Redclift 2002)). The functioning of environmental system was not commonly considered.

Also drawing on the Brundtland Report, SS embeds SD as the goal of sustainability: improving the well-being of humanity requires “development,” although undertaken such as to not overly degrade the capacity of the environment and Earth system to provide the services that maintain the biosphere and to enhance the ecosystem services that underlie many parts of development. Conceptually, however, this usage of SD in the SS literature differs from that in the older and newer SD literatures, because it insists more explicitly on the integration of the human and environmental subsystems as the means of understanding and assessing the problem—a means in which each subsystemfeedbacks on the other with positive or negative consequences, forming a globally interconnected, complex adaptive Anthropocene System (Clark and Harley 2019). In this framing, SD in SS, socioeconomic development is tightly woven with the environment. As an example, the vulnerability or resilience of the social-environmental system includes both subsystems and their interactions with one another (Turner II et al. 2003); neither subsystem should be addressed alone.

Although the earliest root of SD was originally dominated by attention to the ecological subsystem (Lélé 1991, Kidd 1992, Castro 2004), SD in the framing of SS has shifted from greening to improving inclusive human wellbeing, with environment protection as a possible means for, but not the end of, SD (Pearson 2016). Equally importantly, SS has refocused its science-policy interface with that on the knowledge-
action gap, consistent with the intent of Future Earth (https://futureearth.org/). Although the efforts to make science and education of more practical service to society can trace back to SD’s partial root in the reflective studies on science and technology in the late 1960s (Kidd 1992, Turner II 2002, Kates 2011a), SD in the framing of SS has shifted from producing knowledge for action to linking knowledge with action (Clark et al. 2004, Matson et al. 2016). The influences of the early efforts remained disciplinary until the 1990s when transdisciplinarity resurged as a uniting idea at the science-policy interfaces for promoting new forms of knowledge production, to address urgent, complex, and normative global concerns, i.e., the so-called ‘wicked’ sustainability problems (Bernstein 2015, Weichselgartner and Truffer 2015).

Though omitting many founding publications and contributing scholars of SD and SS research, our results consistently indicate that the social-ecological (social-environmental) system perspective and increasingly, also the transdisciplinary perspective—either marginally rooted in SD studies (Figs. 2.2A and 2.3A)—together identify the core of SS (Figs. 2.2B, 2.3B, and 2.4B). United by the call for a useful science to link knowledge and action in the late 1990s (Clark et al. 2004), some of the interdisciplinary SD scholars—the above-mentioned underrepresented older-SD and root-SD scholars (partially identified in Fig. 2.4)—joined the Kate-Clark community (Fig. 2.3B) in building a new human-environmental science under the name of SS (National Research Council 1999, Kates et al. 2001). Through the lens of the philosophy of science, in the building of SS, the social-environmental systems perspective has served as an ontological meta-frame for bridging the many precedent human-environment research
traditions (e.g., human-environmental geography, political ecology, human ecology, landscape ecology, fisheries science, resource economics, environmental economics, ecological economics); while the transdisciplinarity perspective appears to have the potential to serve as a bridging epistemology for integrating various human-environment theories, with action/practice as the ultimate criterion for testing knowledge/truth (Bunge 2003, Scarano 2019).

Our findings support Clark and Dickon’s (Clark and Dickson 2003) suggestion that SS is something different from the conventional SD research, and appear to validate Kates’s (Kates 2011b) claim that SS is a special way of framing the conventional SD studies that involves new theoretical and methodological considerations to create a robust, integrated social-environmental systems approach, crossing the academic-application divide. As the “use-inspired basic research” strand of SD studies (Clark 2007, Clark and Harley 2019), SS is “basic” as characterized by its complex social-environmental systems perspective, and is “use-inspired” as characterized by its transdisciplinary perspective. The conventional SD studies contribute to SS, by zooming into certain parts of the social-environmental system while simplifying or even neglecting other parts, and by mainly providing scientific insights while being minimally normative. From the late 1980s, however, there has been less attention to focused disciplinary SD research (Mebratu 1998) and increasing awareness in the SD community of the special SS dimensions identified by Kates (2011b) and others, including “transdisciplinary” activities bridging research and practice (Turner II et al. 1990), creating a somewhat more closer fit with SS (Mooney 2016). Anchored in the human-environmental sciences, SS
has advanced the complex social-environmental systems orientation for more than a decade and has increasingly entertained the knowledge-action gap (Figs. 2.2D and 2.3B), consistent with the United Nations’ Sustainable Development Goals (United Nations 2015).

Significantly, our results highlight three challenges along our common journey toward sustainability. Firstly, the global SD movement, as dominated by the business-oriented discourse, is faced with a potential science crisis—SD has been losing public attention from 2004 forward, until the launch of Sustainable Development Goals with more SS instilled (Figs. 2.1A, B). Secondly, though with rapidly growing interests from the public and academia, SS is still notably marginal in the SD research landscape (Fig. 2.1). Thirdly, though SD in the framing of SS has recognized improving inclusive human wellbeing as its ultimate goal, voices of the developing world remain to be equally heard (Fig. 2.5). In this contemporary context, the call for further expansion of SS—as the science of and for SD (National Research Council 1999)—has recently been made in order to help “guide the societal transformations necessary to achieve the 2030 Agenda” (p.892) (Messerli et al. 2019). In this regard, we have to move beyond distinguishing SS from the conventional SD research, toward better integrating the two to harness all kinds of knowledge “to meet the great environment and development challenges of this century (Kates 2011b)”—the wicked sustainability problems that are of public interests around the world. Six gaps for better integrating SS and conventional SD research have been proposed by Clark and Harley (2019) very recently. Filling these and other gaps will
depend heavily on the working together of sustainability researchers, practitioners, decision-makers, funders and the civil society.

2.5 Conclusion

We present an evidence-based study to demonstrate that sustainability science (SS) is not simply a new label for conventional sustainable development (SD) research. Multiple bibliometric tools are used to compare and contrast the characteristics of SS and SD research based on keywords, literature development paths, knowledge bases, and country participation. We find that SS is developing into a cohesive human-environmental science that attempts to integrate multi-disciplinary SD studies within the social-environmental system meta-frame, and that SS is increasingly developing a transdisciplinarity character. We also find that SS is growing yet still marginal in the SD research enterprise, which has been largely losing momentum of the public since 2004. Our findings do not dismiss conventional SD research—its diverse perspectives will continue to benefit the global SD movement—rather, we highlight the need to further integrate the diverse and sometimes conflicting conventional SD perspectives with the social-environmental systems and transdisciplinary perspectives of SS.
CHAPTER 3

RESEARCH PROGRESS AND KNOWLEDGE GAPS OF LANDSCAPE SUSTAINABILITY SCIENCE: A MULTIMETHOD BIBLIOMETRIC REVIEW

Abstract

Landscape scientists have increasingly studied sustainability during the past three decades, with a plurality of perspectives and methods. However, a comprehensive review of the relevant literature is still lacking. Two concepts capture the core of these studies: sustainable landscapes (SL) and landscape sustainability (LS). Here we present a bibliometric analysis of 333 English papers published in SCI journals (i.e., indexed by Web of Science) during 1990 – 2017, whose titles, abstracts or keywords contain SL, LS, or both. Using multiple methods, including change-point detection, text and topic mining, and citation analysis, we found: (1) Sustainability studies of landscapes have entered a rapid growth phase since 2004-2006, as determined statistically by the annual publications and citations; (2) There have been many more studies focusing on the ecological and practical dimensions than sociocultural and theoretical dimensions; and (3) Influenced by advances in sustainability research in a broader science context, studies of SL and LS have become increasingly holistic, transdisciplinary, and normative. Our findings suggest that, to further advance landscape sustainability science, scholars need to be more explicit about the underlying sustainability perspective and associated scales of key terms (e.g., SL, LS, and ecosystem services) in specific studies, and need to put more emphasis on place-based case studies of various landscape unsustainability syndromes by
integrating the sustainability science-based social-ecological systems and transdisciplinary perspectives.

3.1 Introduction

Humanity’s pursuit for sustainable development has attracted research from various disciplines (Bettencourt and Kaur 2011); in particular, landscape scientists have been studying sustainability for over three decades (Thayer 1989). In recent years, some scholars have called for a science of landscape sustainability to promote the research and practice of sustainability by focusing on the landscape and regional scales (Wu 2006, Naveh 2007, Wu 2013b). This call has been echoed by professional conferences held (e.g., the annual *International Landscape Sustainability Science Forum* since 2013, the 12th *International Congress of Ecology* in 2017) and growing numbers of publications in peer-reviewed journals (e.g., special issues of *Landscape and Urban Planning*, *Landscape Ecology, Sustainability Science*, and *Sustainability*).

Arguments have been made for how closely landscapes are related to sustainability and how much landscape scientists can offer, particularly the “pivotal” role of landscapes in bridging local and global sustainability, the multi-scale perspective, the spatially explicit approach, and the transdisciplinary tradition (Benson and Roe 2000, Wu 2006, Pearson and McAlpine 2010, Turner 2010, Dramstad and Fjellstad 2011, Wu 2012, Opdam et al. 2018). However, some still doubt the usefulness of even the concepts of sustainable landscapes (SL) and landscape sustainability (LS), due largely to the evolving nature of the concepts and the concern on the possibility of sustaining landscapes in a

---

8 This chapter was written in collaboration with Jianguo Wu and John M. Anderies, and has been published in *Landscape and Urban Planning* (doi: 10.1016/j.landurbplan.2019.05.005).
changing world (Antrop 2006, Selman 2008, Wiens 2013). In this paper, we ask: (1) Are the sustainability studies of landscapes coalescing and developing into a science? Specifically, has the number of such studies been increasing in terms of annual publications and citations? (2) What are their main research topics and themes, and how has their research focus evolved? (3) What are the main challenges and directions for developing an integrative landscape science that can help enhance sustainability? To address the three questions, a timely review of the relevant literature is necessary.

Yet, such a review is no easy job due to the multiple interpretations of landscape (Kalesnik 1961, Antrop 2013) and sustainability (Chichilnisky 1999, Kuhlman and Farrington 2010) and also the consequent challenges of communicating and operationalizing SL and LS (Antrop 2006, Selman 2008, Musacchio 2011, Bell 2012, Wiens 2013, Luc 2015). Traditional literature reviews that are generally ad hoc may run the risk of missing important information and introducing biased interpretations (Qasim 2017). Contrastinglly, bibliometric reviews take less time and are more reproducible, yet may underappreciate the subtle insights in the main body of papers. Combing the two approaches, therefore, we present a quantitative-qualitative review of 333 sampled papers that explicitly used the terms of SL and/or LS in their titles, abstracts, or keywords.

The remainder of the paper is organized as follows: Section 3.2 provides the methodological details; Section 3.3 compares and contrasts the concepts of SL and LS based on our literature review, in terms of their temporal trends of publications and citations, research topics and themes, knowledge bases, and literature development paths; Section 3.4 addresses the above-mentioned three research questions, and discusses the
main progress, challenges, and new perspectives in the field of landscape sustainability; and Section 3.5 concludes with major findings and future directions. We hope that this review will help clarify the two core concepts in the science and practice of landscape sustainability, stimulate new research opportunities, and further promote the transdisciplinary integration among landscape ecology, land system science, and sustainability science.

3.2 Materials and Methods

3.2.1 Literature Search and Data Processing

We conducted a literature search on July 7th, 2018 using Web of Science Core Collection (WoS). Though less comprehensive than some other popular bibliographic databases (e.g., Scopus and Google Scholar), WoS covers Science Citation Index Expanded and Social Sciences Citation Index journals and is widely used in the academic world. By searching “sustainable landscape” OR “sustainable landscapes” (sustainable landscape(s) hereafter) in the titles, abstracts, or keywords of the WoS English papers published before 2018, we obtained 273 SL papers. Similarly, by searching “landscape sustainability” we sampled 68 LS papers. The two subsets of papers were then combined, resulting in a whole set of 333 papers. Bibliographic information of each sampled paper was saved for quantitative analyses, including trend and changepoint detection, text and topic mining, and citation analysis. The full texts of seminal publications identified in citation analysis were reviewed to explore how the research has evolved.
3.2.2 Trend and Changepoint Detection

To determine the trend and potential change points of the sustainability studies of landscapes, we used Mann-Kendall test and Pettitt’s test (Li et al. 2017, Fang et al. 2018). The \texttt{mk.test} and \texttt{pettitt.test} functions of \textit{trend R Package} were applied to six time series: the annual publications and annual citations of the three collections of papers (i.e., SL, LS and the whole). Their trends were displayed using the \textit{geom\_smooth} function of \textit{ggplot2 R Package}, by the default \textit{loess} regression method (Wickham and Grolemund 2016). To determine the correlation between the SL and LS studies, we did Shapiro-Wilk normality test using the \texttt{shapiro.test} and \texttt{ggplot} functions, and then calculated Spearman correlation coefficients by using the \texttt{cor.test} function (Wickham and Grolemund 2016).

3.2.3 Text and Topic Mining

Bibliometric methods for text mining were used to explore the research topics and their linkages of the 273 SL and 68 LS papers, separately. First, to uncover the most prominent topics, we extracted two-word, three-word and four-word phrases from the \textit{titles}, \textit{abstracts}, and \textit{keywords} of the selected papers, with their counts recorded (available at \url{http://www.writewords.org.uk/phrase_count.asp}); after removing stop words and grouping word variations, the resulting phrase count lists were then visualized as wordclouds (available at \url{https://www.wordclouds.com/}). Second, to detect the structure of the field’s research landscape, we mapped the linkages and clustering of topics extracted from the text corpora of \textit{keywords} and those of \textit{titles and abstracts}, separately. The topic clustering map based on \textit{keywords} was generated using the \textit{conceptualStructure} function of \textit{Bibliometrix R Package} (Aria and Cuccurullo 2017), and interpreted as the
structure of *expressed* topics, for they are from phrases highlighted explicitly by the authors. The map based on *titles and abstracts* was generated using the *VOSviewer* software (van Eck and Waltman 2010), and interpreted as the structure of *latent* topics, for they are embedded implicitly in titles and abstracts but not authors’ self-identified topics. The comparative research design (i.e., expressed topics versus latent topics) was intended to cross-validate the topic mining results and help depict the field’s multi-facet image.

### 3.2.4 Citation Analysis

To explore the knowledge bases (Buter and Van Raan 2013) of the 333 sampled papers, we used *HistCite™* (Garfield et al. 2006) for identifying the top 10 out-of-sample publications that were most-cited by the SL and LS papers. We also used *HistCite™* to explore the field’s development paths, by mapping the citation linkages between the top 20 papers that received the most citations from within the collection (i.e., local citations, as called in *HistCite™*). The full-texts of those most-cited publications, out-of-sample and within-sample, were reviewed qualitatively in the traditional manner.

### 3.3 Results

#### 3.3.1 Rapidly Growing Interest in Sustainability Studies of Landscapes

There were on average 12 papers published annually, each getting 0.73 times cited per year (Table 3.1). Those papers were published in 141 journals by 1009 scholars, 93% of whom collaborated on their sustainability research. Interestingly, the 273 SL and 68 LS papers share only 8 duplicates that mention both concepts (for details refer to Table S1). The numbers of publications, journals, and authors for the SL papers are four times
those of the LS papers; while the latter received more citations per article and involved more collaborations. Published in *Landscape and Urban Planning*, the earliest sampled LS paper (Rodiek and DelGuidice 1994) was four years younger than the earliest sampled SL paper (Steinitz 1990). Neither of the two papers defined SL or LS, however. Although both were associated with ecological integrity and biological diversity, SL seemed more pragmatic and less theoretical than LS. With the similarities and differences in mind, the analysis of the following results is both comparative and synthetic.

**Table 3.1**
Overview of the sampled papers on sustainability studies of landscapes. Papers were collected on 07/07/2018 from Web of Science Core Collection (WoS). The sampling was based on search for key terms in titles, abstracts, and keywords. The search was limited to WoS papers that were written in English and published before 2018. The second column shows the characteristics of one subset of papers that were searched using “*sustainable landscape(s)*” OR “*sustainable landscapes*” as the query term; the third column is for another subset of papers searched using “*landscape sustainability*”; and the last column displays the features of the whole data set by combining the two subsets.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of articles</td>
<td>273</td>
<td>68</td>
<td>333</td>
</tr>
<tr>
<td>Number of journals</td>
<td>127</td>
<td>30</td>
<td>141</td>
</tr>
<tr>
<td>Number of authors</td>
<td>838</td>
<td>225</td>
<td>1009</td>
</tr>
<tr>
<td>Average citations per article</td>
<td>19.68</td>
<td>23.1</td>
<td>20.64</td>
</tr>
<tr>
<td>Authors per article</td>
<td>3.07</td>
<td>3.31</td>
<td>3.03</td>
</tr>
<tr>
<td>Authors of single authored articles</td>
<td>63</td>
<td>14</td>
<td>70</td>
</tr>
<tr>
<td>Authors of multi authored articles</td>
<td>775</td>
<td>211</td>
<td>939</td>
</tr>
<tr>
<td>Collaboration Index*</td>
<td>3.82</td>
<td>4.59</td>
<td>3.86</td>
</tr>
</tbody>
</table>

*Note: Collaboration Index is calculated as the total number of authors of multi-authored articles divided by the total number of multi-authored articles.*

The trend and change-point detections of annual publications of the three paper collections (i.e., SL, LS, and the whole set) all show that there has been rapidly growing interest in studying the sustainability of landscapes since especially 2006 (Figure 3.1A).
Also, annual citations to the three paper collections all show a growing trend, with the probable take-off time for almost exponential growth detected to be 2004 (Figure 3.1B). The consistency in the trends of the SL and LS papers is confirmed by their statistically significant correlations in terms of both annual publications and citations (Figures 3.1C-D). The main point of Figure 3.1 is that, sustainability studies of landscapes have been growing significantly since 2004-2006, in terms of both research output and citation.
Figure 3.1 The number of papers with “sustainable landscape(s)” or “landscape sustainability” in their titles, abstracts, and keywords, and the number of citations to the papers of each category. (A) and (B) show the temporal trends and change-points of the sampled papers in terms of annual publications and annual citations, respectively; (C) and (D) illustrate the correlation between the two subsets of sampled papers, with the lines of best fit highlighted.

3.3.2 Multi-Facet Research Topics and Themes

As to the research topics that were identified from the titles, abstracts, and keywords (Figure 3.2), the SL and LS papers have much in common yet differ subtly. On one hand, they share topics including ecosystem services, landscape ecology, landscape planning, and agricultural landscape. On the other hand, in the LS studies, some new
topics appear like climate change, social-ecological systems, conceptual framework, and urban landscape; some topics receive much more attention, such as ecosystem services and landscape ecology; some are noticeably less researched, like case studies, landscape management, and landscape development. Particularly, the topic explicitly related to sustainability seems to have experienced a transition— from sustainable development in the SL studies to sustainability science in the LS studies.

**Notes:**
- Generated in [https://www.wordclouds.com/](https://www.wordclouds.com/)
- Phrases were extracted from title, abstract and keywords of the selected papers
- Color is for visibility; phrase size is proportionate to each phrase’s relative frequency and comparable between the left and right panels

![Wordclouds](image)

**Figure 3.2** Wordclouds of the topics identified from the titles, abstracts, author’s keywords, and ISI keywords plus of the two subsets of papers that were sampled by searching (A) “sustainable landscape(s)” or (B) “landscape sustainability”, respectively. Wordclouds of phrases usually make better sense than those of single words (Bettencourt and Kaur 2011).

Regarding the manifested research themes that were indicated by the clusters of co-occurring topics in author’s keywords (Figure 3.3), the SL and LS studies show clearer contrast. The SL papers focus mostly on landscape ecology research (i.e., cluster 1), while some on sustainability governance in particular case studies (i.e., cluster 2) and
some others on the effectiveness of community forestry in preventing deforestation (i.e., cluster 3). Contrastingly, the LS papers contain only a few intensively studied themes, focusing on landscape planning of ecosystem services (i.e., cluster 3), landscape and sustainability (i.e., cluster 2), and linkages between LS and biodiversity (i.e., cluster 1). In general, Figure 3.3 suggests that the SL studies focus more on ecological/landscape planning but less on sociocultural dimensions, and that the LS studies also have a strong ecological/landscape planning focus but without a detectable sociocultural focus.

![Figure 3.3](image.png)

**Figure 3.3** Clustering of the topics identified from the *author’s keywords* of the two subsets of papers that were sampled by searching (A) “sustainable landscape(s)” or (B) “landscape sustainability”, respectively. Both graphs were generated by multiple correspondence analysis of the identified topics using the *conceptualStructure* function of the *Bibliometrix R Package*; clusters express common themes (Aria and Cuccurullo 2017).

The contrasting patterns of the clusters of co-occurring topics in the *titles* and *abstracts* of the two subsets of papers (Figure 3.4) show that the latent research themes of SL and LS are indeed diverging. In the SL studies, there are five thematic clusters (Figure 3.4A): the cluster of community forestry/forest sustainability; the cluster of landscape pattern and habitat conservation; the cluster of people-nature relationships and
problem-driven landscape management; the cluster of the factors and indicators for assessing ecosystem services, especially on farms; and the cluster of the perception and evaluation of landscape benefits and services. In the LS studies, there are three thematic clusters (Figure 3.4B): the cluster of people-nature relationships and ecosystem services; the cluster of LS approaches and conceptual frameworks; and the cluster highlighting specific study areas. To recap, the SL and LS studies share the research theme of ecosystem services and people-nature relationships, and the SL studies have more diverse themes and are more pragmatic than the LS studies.

Figure 3.4 Clustering of the topics identified from the titles and abstracts of the two subsets of papers: (A) “sustainable landscape(s)” and (B) “landscape sustainability”, respectively. Both networks were generated by multiple correspondence analysis with VOSviewer.

3.3.3 Evolution Toward an Increasingly Transdisciplinary Research Field

Changing knowledge bases of the two research domains

The existing studies draw most insights from landscape ecology, for 18 out of the 23 most-cited publications have landscape ecologists as their leading authors (Table 3.2).
The SL studies draw new ideas more from ecological economics, with their 3 most-cited publications that were not contributed by landscape ecologists all on defining and evaluating ecosystem services (Costanza et al. 1997, Daily 1997, de Groot et al. 2002).

On the other hand, the LS studies draw new ideas more from sustainability science, with their 2 most-cited publications that were not contributed by landscape ecologists focusing on the fundamentals of sustainability science (Kates et al. 2001) and resilience thinking for sustainability (Walker and Salt 2006).

**Table 3.2**  
Most-cited publications by the papers sampled via searching “sustainable landscape*” and “landscape sustainability”, respectively.

<table>
<thead>
<tr>
<th>Sampled papers</th>
<th>Most-cited publications</th>
<th>Title</th>
<th>Source</th>
<th>Cited frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainable landscape(s)</td>
<td></td>
<td>Land Mosaics: The Ecology of Landscapes and Regions</td>
<td>Cambridge University Press</td>
<td>8.42%</td>
</tr>
<tr>
<td>Forman 1995</td>
<td></td>
<td>The value of the world's ecosystem services and natural capital</td>
<td>Nature</td>
<td>5.86%</td>
</tr>
<tr>
<td>Costanza et al. 1997</td>
<td></td>
<td>Landscape Ecology</td>
<td>Wiley</td>
<td>5.13%</td>
</tr>
<tr>
<td>Forman &amp; Godron 1986</td>
<td></td>
<td>Sustainable development and sustainable landscapes: Defining a new paradigm for landscape ecology</td>
<td>Fennia</td>
<td>4.76%</td>
</tr>
<tr>
<td>Haines-Young 2000</td>
<td></td>
<td>Applying landscape ecological concepts and metrics in sustainable landscape planning</td>
<td>Landscape and Urban Planning</td>
<td>4.76%</td>
</tr>
<tr>
<td>Leitao &amp; Ahern 2002</td>
<td></td>
<td>Design in science: extending the landscape ecology paradigm</td>
<td>Landscape Ecology</td>
<td>4.40%</td>
</tr>
<tr>
<td>Nassauer &amp; Opdam 2008</td>
<td></td>
<td>Key issues and research priorities in landscape ecology: An idiosyncratic synthesis</td>
<td>Landscape Ecology</td>
<td>4.40%</td>
</tr>
<tr>
<td>Wu &amp; Hobbs 2002</td>
<td></td>
<td>A typology for the classification, description and valuation of ecosystem functions, goods and services</td>
<td>Ecological Economics</td>
<td>3.30%</td>
</tr>
<tr>
<td>De Groot et al. 2002</td>
<td></td>
<td>Nature's Services: Societal Dependence on Natural Ecosystems</td>
<td>Island Press</td>
<td>4.03%</td>
</tr>
<tr>
<td>Daily 1997</td>
<td></td>
<td>Landscape ecology, cross-disciplinarity, and sustainability science</td>
<td>Landscape Ecology</td>
<td>4.03%</td>
</tr>
<tr>
<td>Wu 2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Authors</td>
<td>Title</td>
<td>Journal</td>
<td>Percentage</td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>--------------------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>Termorshuizen &amp; Opdam 2009</td>
<td>Landscape services as a bridge between landscape ecology and sustainable development</td>
<td>Landscape Ecology</td>
<td>17.65%</td>
<td></td>
</tr>
<tr>
<td>Wu 2006</td>
<td>Landscape ecology, cross-disciplinarity, and sustainability science</td>
<td>Landscape Ecology</td>
<td>16.18%</td>
<td></td>
</tr>
<tr>
<td>Nassauer &amp; Opdam 2008</td>
<td>Design in science: extending the landscape ecology paradigm</td>
<td>Landscape Ecology</td>
<td>14.71%</td>
<td></td>
</tr>
<tr>
<td>Kates et al. 2001</td>
<td>Sustainability science</td>
<td>Science</td>
<td>13.24%</td>
<td></td>
</tr>
<tr>
<td>Naveh 2007</td>
<td>Landscape ecology and sustainability</td>
<td>Landscape Ecology</td>
<td>13.24%</td>
<td></td>
</tr>
<tr>
<td>Cumming 2011</td>
<td>Spatial resilience: integrating landscape ecology, resilience, and sustainability</td>
<td>Landscape Ecology</td>
<td>10.29%</td>
<td></td>
</tr>
<tr>
<td>Forman 1995</td>
<td>Land mosaics: The ecology of landscapes and regions</td>
<td>Cambridge University Press</td>
<td>10.29%</td>
<td></td>
</tr>
<tr>
<td>Gobster et al. 2007</td>
<td>The shared landscape: what does aesthetics have to do with ecology?</td>
<td>Landscape Ecology</td>
<td>10.29%</td>
<td></td>
</tr>
<tr>
<td>Potschin &amp; Haines-Young 2006</td>
<td>Landscapes and sustainability</td>
<td>Landscape and Urban Planning</td>
<td>10.29%</td>
<td></td>
</tr>
<tr>
<td>Potschin &amp; Haines-Young 2013</td>
<td>Landscapes, sustainability and the place-based analysis of ecosystem services</td>
<td>Landscape Ecology</td>
<td>10.29%</td>
<td></td>
</tr>
<tr>
<td>Turner &amp; Gardner 2001</td>
<td>Landscape Ecology in Theory and Practice</td>
<td>Springer</td>
<td>10.29%</td>
<td></td>
</tr>
<tr>
<td>Walker &amp; Salt 2006</td>
<td>Resilience Thinking: Sustaining People and Ecosystems in a Changing World</td>
<td>Island Press</td>
<td>10.29%</td>
<td></td>
</tr>
<tr>
<td>Wu 2008</td>
<td>Making the case for landscape ecology an effective approach to urban sustainability</td>
<td>Landscape Journal</td>
<td>10.29%</td>
<td></td>
</tr>
</tbody>
</table>

As for the 18 most-cited publications from landscape ecologists, two observations are worth noting in terms of their similarities and differences for the SL and LS papers that cited them. For the similarities, three papers were co-cited by the SL and LS papers: Forman’s book laid the foundation of landscape ecological thinking based on the patch-corridor-matrix paradigm (Forman 1995); Wu (2006) proposed six reasons why landscape ecology can and should contribute to the scientific core of sustainability science by transforming into a more transdisciplinary science; Nassauer and Opdam
incorporated the design perspective into the classic pattern-process paradigm (i.e., an updated version of the patch-corridor-matrix paradigm), and proposed the design-in-science paradigm (i.e., might also be called the pattern-process-value paradigm) to help transform landscape ecology into more of a transdisciplinary science. Moreover, the SL and LS papers also draw insights from each other (Table 2): the SL papers cited Wu and Hobbs (2002) while the LS papers cited Potschin and Haines-Young (2006b) and Termorshuizen and Opdam (2009).

There are subtle differences, however (Table 3.2). To some extent, the SL papers seem to have been inspired by the patch-corridor-matrix model in landscape ecology (Forman and Godron 1986), with interests in applying landscape metrics in assessing the ecological sustainability of landscape planning (Leitao and Ahern 2002) and in developing a landscape-based ecosystem services approach (Haines-Young 2000). The earlier LS papers grew upon an updated version of the patch-corridor-matrix paradigm that is pattern-based and more quantitative – the pattern-process paradigm (Turner and Gardner 2001); they revisited the aesthetics-ecology relationship debate (Gobster et al. 2007), witnessed the resurgence of the cultural dimension of landscape studies that have been redirecting landscape ecology back to its holistic tradition (Naveh 2007), and called for integrating landscape ecology with planning, design, and other social sciences to develop a transdisciplinary science of landscape and sustainability (Naveh 2007, Wu 2008). For the other two most-cited papers by the LS studies, one proposed spatial resilience to bridge landscape ecology and sustainability (Cumming, 2011), the other
reflected on the pros and cons of existing three approaches to operationalizing the idea of ecosystem services (Potschin and Haines-Young 2013).

*Converging literature development paths of the two research domains*

A research community of SL and LS studies seems to be emerging, as evidenced by the citation network of the top 20 papers that are most-cited within the 333 collected papers (Figure 3.5, for details refer to Table S3.2). The network contains a dominant sub-network with 13 of the 20 keystone papers linked together, a much smaller sub-network with only 4 interlinked, and 3 disconnected papers. Figure 3.5 suggests that sustainability studies of landscapes have formed a rather cohesive field where most scholars talk to each other (i.e., the dominant sub-network), although a smaller group has a different conversation (i.e., the right-side small sub-network) and some voices are less well-heard in the main discourses (i.e., the 3 isolated papers). Embedded in the dominant sub-network are all the 4 mapped LS papers citing and cited by some SL papers, which confirms with Figures 3.1C-D and 3.2-3.4 that SL and LS studies are the two sides of the same “coin.” Also, Figure 3.5 agrees with Figure 3.1A in that this field gained special momentum in 2006. New in Figure 3.5 is that a confluence of existing studies probably occurred in 2013, though insights from the small group conversation and isolated studies were not recognized.
Figure 3.5 Literature development paths of all the 333 collected papers on sustainability studies of landscapes. Arrows refer to citations. Node size is in proportion to a paper’s total cites by other sampled papers (i.e., Local Citation Score, sensu HistCite™). Mapped papers are restricted to those with local citations ranking in the top 20. The network of local citations is more suitable than that of global citations (i.e., by all papers archived in Web of Science Core Collection) for identifying the internal structure of a research field (Garfield et al. 2006).
Digging into the full texts of the 20 keystone papers (Figure 3.5) helps understand how their research focus has evolved. The earliest papers did not cite each other and sowed independently the seeds of the field. The concept of SL was initially adopted as the goal of reconciling the aesthetics-ecology trade-offs in developing landscapes (Steinitz 1990, Nohl 2001); the usefulness of greenway networks in protecting ecological integrity was discussed (Ahern 1995); the importance of studying landscape conservation and sustainability was recognized at the US-IALE annual symposium in 2001, when the concept of LS started to be known (Wu and Hobbs 2002).

The early seeds had not broken above the soil until 2006, when *Landscape and Urban Planning* published a special issue (Potschin and Haines-Young 2006b) that produced four keystone papers. Among them, Antrop (2006) pointed out the growing ecological awareness in scenic landscape design and brought the interpretive multiplicity of SL to attention. He argued that sustaining optimized landscape patterns in a changing world is utopian and that SL should be context-specific, value-laden, evolutionary, and transdisciplinary. Potschin and Haines-Young (2006a) elaborated on the ecosystem services-based paradigm to operationalize SL, and argued that a key topic for future research should be “an exploration of the ‘sustainability choice space’ defined by the interaction of biophysical limits and social and economic values at the landscape-scale.” Blaschke (2006) commented that the ecosystem services and SL paradigm was not mature and that the classic patch-corridor-matrix paradigm could help spatialize sustainability, and he agreed that future research should focus on exploring the “sustainability choice space” and further suggested the need to develop “integrated yet
Opdam et al. (2006) integrated the patch-corridor-matrix paradigm and value-laden landscape planning, and proposed ecological network as an instrumental tool for bridging the paradox between nature conservation and landscape development. This idea of ecological network was further developed into a framework that incorporates ecological indicators into decision-making (Termorshuizen et al. 2007). Along this line of research that emphasizes ecological principles in decision-making, landscape services was coined as a conceptual tool for bridging landscape ecology and sustainable development (Termorshuizen and Opdam 2009).

Since 2009, as the “trunks” of the field have developed further and the “seedlings” have started to grow into “saplings”, theoretical studies have gained more attention. After years of instilling landscape ecological principles into SL studies, there seemed to be a return to recognizing the sociocultural dimension of landscapes when speaking of LS (Musacchio 2009a). By decomposing the complexity of human-nature interactions, Musacchio (2009b) proposed the six Es (i.e., environment, economic, equity, aesthetics, experience, and ethics) conceptualization of LS. To overcome “the grand challenge” of operationalizing LS, the design-in-science/pattern-process-value paradigm (Nassauer and Opdam 2008) was promoted (Musacchio 2011). A “little woods” started to form at 2013 when Landscape Ecology published a special issue (Musacchio 2013), in which Wu (2013b) elaborated on some core concepts of sustainability, and proposed landscape sustainability science by integrating landscape ecology with sustainability science based on landscape pattern and MEA’s ecosystem services-human wellbeing framework (Millennium Ecosystem Assessment 2005).
Isolated from the above research “woods”, there were 4 papers focusing on the institutional governance of community forestry for forest sustainability and biodiversity conservation (Bray et al. 2003, Bray et al. 2004, Dalle et al. 2006, Ellis and Porter-Bolland 2008) which is consistent with Figures 3.3-3.4. One paper highlighted the importance of spatializing land-management (Mottet et al. 2006), and another paper advocated a social-ecological systems perspective for planning landscapes for sustainability (Bohnet and Smith 2007). However, these 6 keystone papers have not been well integrated into the mainstream.

The qualitative review is consistent with the quantitative review results (Figures 3.1-3.4), showing that a new research field has been emerging from landscape ecology, with influences from ecological economics and sustainability science. Particularly, the qualitative review shows that sustainability studies of landscapes have been evolving toward a more transdisciplinary field with growing recognition of the sociocultural dimension of landscapes and increasing theoretical studies.

3.4 Discussion

Based on the trend analysis of research interest, the bibliometric text mining of research topics and themes, and the bibliometrics-based full-text review of seminal papers, now we can address the three research questions that we lay out in the Introduction section. These questions are relevant for discussing the status quo and future directions of the emerging field of sustainability studies of landscapes.
3.4.1 Progress and Challenges: Where Are We Now?

Our analysis shows that the quantity and quality (Ding et al. 2014) of sustainability studies of landscapes have increased significantly since 2004-2006 (Figures 3.1 and 3.5), with a rapid growth in publications and citations as well as related journals and contributing authors (Table 3.1). Although the increasing research activities on SL and LS may be attributable partly to the ever-expanding scientific literature in general, its burst point between 2004 and 2006 indicates that the field has entered a new development phase with a greater momentum. Also, a confluence of SL and LS studies appears to have begun around 2013 (Figure 3.5) when landscape sustainability science was proposed (Wu 2013b). Are sustainability studies of landscapes coalescing and developing toward an integrative science? The answer seems affirmative.

Landscape sustainability science is rooted in landscape ecology (Table 3.2, Figures 3.2-3.5), but goes beyond it. With theories and methods from landscape ecology, landscape sustainability science has a unique research niche to help enhance ecological sustainability, operationalize the spatial dimension of sustainability, and understand the upscaling of sustainability (Leitao and Ahern 2002, Wu 2006, Turner 2010, Opdam et al. 2018). More importantly, there has been increasing recognition of the waning sociocultural tradition within the landscape profession (Naveh 2007, Nassauer and Opdam 2008, Wu 2008, Musacchio 2009a, Wu 2010, 2011), exemplified by the “pattern-process-value” paradigm (Nassauer and Opdam 2008, Termorshuizen and Opdam 2009) and the more detailed “landscape pattern- biodiversity/ecosystem function-ecosystem services-human wellbeing” framework (Wu 2013b). Recent studies, in line with the
ideas of the not well-recognized, earlier SL and LS papers in Figure 3.5 (Rodiek and DelGuidice 1994, Bray et al. 2003, Bray et al. 2004, Dalle et al. 2006, Bohnet and Smith 2007, Ellis and Porter-Bolland 2008), further highlight the role of human values and institutional governance in landscape design and management for sustainability (Bürgi et al. 2017b, Foo et al. 2018, Opdam 2018). In retrospect, it is the perspective shift in sustainability studies of landscapes from mostly ecological to more social-ecological that led to the emergence of landscape sustainability science.

At least two major challenges must be addressed to advance landscape sustainability science. First, before any research field grows into an established science, a necessary (but not sufficient) condition is that the field shares clearly defined terminologies. Unfortunately, the two core concepts of landscape sustainability science, SL and LS, have long suffered from interpretative multiplicity and remained debated (Antrop 2006, Selman 2008, Wiens 2013). Initially, the concept of SL was adopted to mean landscapes being ecologically sustainable (Forman 1990) as renewable natural capital. Later SL gained more dimensions, referring to landscapes being multifunctionally sustainable (Selman 2008, Musacchio 2009b, Luc 2015) in providing ecosystem services. The concept of LS may mean the sustainability of a landscape’s capacity in delivering multi-dimensional services (Doxon 1996) or sustaining and improving human and societal wellbeing (Wiens 2013, Wu 2013b). The multiple interpretations of SL and LS have been met with the pluralistic uses of the ecosystem services concept (Figures 3.2-3.4), which ranges from the habitat-based operationalization (i.e., natural capital stocks) to process-based (i.e., ecosystem services flows), and to place-based (i.e., value-laden trade-
offs and synergies of ecosystem services flows, or say, human wellbeing) (Potschin and Haines-Young 2013).

Epistemological divergence affects methodology, as captured in the three landscape approaches that have been proposed to help enhance sustainability – from landscape conservation for SL (Haines-Young 2000) based on the classic patch-matrix-corridor paradigm (Forman and Godron 1986), to landscape planning for SL/LS (Potschin and Haines-Young 2006a) based on the pattern-process paradigm (Turner and Gardner 2001), and to landscape design for LS (Nassauer and Opdam 2008) based on the pattern-process-value paradigm (Termorshuizen and Opdam 2009). Underlying the epistemological and methodological divergences is a question fundamental to attaining sustainability: “What is to be sustained? (National Research Council 1999, Kates et al. 2005)” – sustainability of natural capital stocks (i.e., landscape structure and function), or sustainability of ecosystem services flows (i.e., landscape-society interactions), or sustainability of human wellbeing (i.e., landscape outcomes and values)? These sustainability perspectives, ranging from absurdly strong sustainability to strong sustainability and to weak sustainability, may all be useful when viewed at different scales (Wu 2013b). Therefore, it is highly recommended to be explicit about the underlying sustainability perspective and associated scale when using the terminologies of SL, SL, and ecosystem services in specific studies.

The second challenge is to enhance the scientific foundation of landscape sustainability science through “place-based research that integrates ecology with
planning, design, and other social sciences (Wu 2008).” Though increasingly emphasizing the sociocultural dimension of sustainability and the need of more science (Musacchio 2009b, a), existing sustainability studies of landscapes are inadequate in taking the social-ecological perspective to conduct place-based research that can produce generalizable knowledge. Contrastingly, land system science has long studied land use transitions and underlying social-ecological drivers and sustainability outcomes (Lambin et al. 2001, Foley et al. 2005). Landscape patterns may provide “X-rays” of dynamic social-ecological systems (Barton 2014) which can show the underlying social-ecological feedback loops (Anderies 2015) for land system architecture to facilitate sustainability transitions (Verburg et al. 2015, Turner II 2016, Turner II et al. 2016).

Recent efforts have attempted to integrate the more “ecological” and pattern-based landscape ecology with the more “social” and process-oriented land system science (Huang et al. 2018, Oberlack et al. 2018, Vadjunec et al. 2018), which shows the potential of facilitating the convergence of the currently two isolated literature development paths (Figure 3.5). Still, further study is needed. For instance, the role of pluralistic human values in determining “sustainability choice space (Potschin and Haines-Young 2006a),” especially its spatial dimension, remains underexplored. Further, little attention has been paid to the governance of landscapes as partial common pool resources and the implications for scaling from local to regional and global sustainability (Levin 2015). For landscape sustainability science to move forward, it needs to continue to emphasize both “linking knowledge to action” and “understanding human-

### 3.4.2 Perspectives from Sustainability Science for Moving Forward

To advance landscape sustainability science, new perspectives, in addition to those from landscape ecology (Turner 2010, Wu 2012, Opdam et al. 2018), are needed. The need is especially urgent given the ecological and pragmatic focuses of the existing SL and LS studies (Figures 3.2-3.5). A recent review (Fang et al. 2018) reveals that sustainability science has entered a maturing stage, indicating new emerging perspectives ripe for reexamining some of the key concepts and research priorities of landscape sustainability science. Discussed below are implications from the social-ecological systems and transdisciplinary perspectives, as revealed in Chapter 2 and other studies (Kates et al. 2001, Kates 2011b, Fang et al. 2018).

The term, social-ecological systems, conveys the idea of humans-in-nature instead of humans-above-nature (Berkes et al. 2000). The social-ecological systems perspective is transformative in its emphasis of system-level sustainability instead of merely the sustainability of a subsystem or dimension of social-ecological systems. Similar to the case of corporate sustainability (Anderies et al. 2013), attaching "sustainability" to systems or system characteristics, either as an adjective as in "SL" or as a noun as in "LS," may not be productive if the big picture is lost (Anderies 2015). While sustainable social-ecological systems share basic principles, every unsustainable social-ecological system can have its own unsustainability challenge. To some extent, landscape is to social-ecological systems what skin is to human bodies. Although a healthy skin alone
cannot guarantee a healthy person, a skin disease may be a symptom of more complex health problems. Therefore, we need to move beyond semantics (Anderies et al. 2013) and focus on a core research task: identifying recurrent landscape “unsustainability syndromes” (WBGU – German Advisory Council on Global Change 1997, National Research Council 1999), uncovering the underlying social-ecological feedback loops, and providing social-ecological solutions that are relevant to landscapes.

The term, transdisciplinary, was coined to convey the idea of crossing academic boundaries and including non-academic stakeholders in doing science (Tress et al. 2004). The transdisciplinary perspective is essential to sustainability science in that the ultimate goal of any sustainability study is to enhance the sustainability of human wellbeing (Meadows 1998, Wiens 2013, Wu 2013b). Being transdisciplinary requires that sustainability studies respect people as their starting and ending points. Although landscape professionals have long practiced site- and local-scale participatory research (i.e., starting with recognizing human needs), the science behind stakeholders’ decision-making in modifying landscapes (i.e., ending with shaping human behaviors) remains insufficient. An important reason is the difficulty in adequately understanding any sustainability decision-making context (i.e., how decisions translate into outcomes) that is characterized by collective action dilemmas, endogenous social-ecological dynamics, complexity, nonlinearities, uncertainty, irreversibility, and critical thresholds (Anderies et al. 2013). In the case of landscape unsustainability syndromes, it remains severely understudied how collective action dilemmas (Ostrom 1990, Anderies and Janssen 2016)
cause social-ecological regime shifts (Kull et al. 2017) and associated landscape degradations (Li et al. 2017).

Integration of the social-ecological systems and transdisciplinary perspectives suggest new questions, in addition to those previously proposed (Musacchio 2013, Turner et al. 2013), for landscape sustainability science to move forward. Consider the tragedy of the Barabaig pastoral landscape degradation in northern Tanzania in the 1980s, due to a new landscape development plan adopted by the government (Lane 1992). The aim was to replace the indigenous semi-nomadic pastoralism with a Canadian-aided wheat-growing scheme, which was supposed to be ecological and more economical. However, without fair recognition of the sociocultural traditions of pastoralism (e.g., seasonal grazing rotation and religious migration), the plan was never implemented as “planned” because the pastoral communities were unable to adapt as hoped. The social-ecological system collapsed with the pastoral landscape degrading and the pastoralists’ wellbeing declining. These examples of landscape unsustainability beget the following questions: 1) What unsustainability problems, be they environmental, social, or economic, had been complained about by stakeholders? 2) What landscape symptoms, i.e., regularities of landscape pattern change, could be identified during the unsustainability trajectory? 3) What were the controlling social-ecological feedback loops that gave rise to the landscape symptoms and associated unsustainability complaints? 4) What was the stakeholders’ sustainability vision in terms of the system’s social-ecological safe-operating-space? 5) What policy prescriptions could be implemented to cure the unsustainability syndrome and achieve a transition to the envisioned sustainable future?
To address the above questions, agent-based modeling (Parker et al. 2002, Janssen and Ostrom 2006), especially pattern-oriented agent-based modeling (Grimm and Berger 2003, Grimm et al. 2005), offers a promising methodology. It can be used to detect the micro social-ecological processes that underlie macro landscape patterns (Schröder and Seppelt 2006, Valbuena et al. 2010), and further, design social-ecological architectures that consider human values, decision-making, governance, and uncertainties (Janssen et al. 2009, Janssen and Baggio 2016). Progress along this line of research has recently been made (Castella et al. 2007, Castella and Verburg 2007, Gaube et al. 2009, Le et al. 2010, Miyasaka et al. 2017), but more are to be explored to help prevent Barabaig tragedies from happening again.

3.5 Conclusion

Sustainability studies of landscapes have evolved into a vibrant research field, especially since 2004-2006. Our bibliometric analysis indicates that landscape ecology, ecological economics, and sustainability science are major contributors to this emerging field. Existing studies, with a strong ecological and practical focus, increasingly recognize the importance of the sociocultural and theoretical dimensions of sustainability. Sustainable landscapes and landscape sustainability have been two core concepts—the two sides of the same coin—with the former being more frequently used in a practical context and in design and planning fields and the latter being more commonly used in a research context and in ecological and environmental sciences. To advance landscape sustainability science, we need to explicitly express the underlying sustainability perspective and associated scales when communicating the ideas of SL and LS and
conducting place-based studies to produce actionable and generalizable knowledge. In addition, we suggest that a transdisciplinary “syndrome-based approach” (i.e., the problem-driven, diagnostic approach, sensu Fig. 1.1, Chapter 1) by focusing on the diagnosis and prognosis of various landscape unsustainability syndromes, can be an effective way of moving the science and practice of landscape sustainability forward.
CHAPTER 4

URBANIZATION-ASSOCIATED FARMLAND LOSS IN CORE AND PERIPHERY AREAS: A MACRO-MICRO COMPARATIVE STUDY IN CHINA

Abstract

The worldwide urbanization-associated farmland loss (UAFL) has led to a decades-long debate on whether/how to protect farmland for food security, or to be more precise, regional and global food self-sufficiency. Yet, existing studies often adopt a narrow framing that urban encroachment of farmland threatens food security. In this chapter, we proposed an analytical framework that goes beyond urban encroachment of farmland, by highlighting four types of UAFL each with different social-environmental causes and consequences. We comparatively analyzed the land use/land cover data of southeast and northwest China, and contrasted field surveys in two representative villages, one rural and the other peri-urban. Our key findings are as follows: (1) The percentage of farmland loss to urban encroachment remained below one third in the southeast urban China during 2000-2015, and increased in the northwest rural China from below one tenth before 2010 to about one fourth thereafter. (2) Urban encroachment of farmland was held to blame by 14.89% surveyed peri-urban farmers and 1.92% rural farmers for reducing grain-production; 29.79% peri-urban and 36.54% rural households converted farmland for residential use during 2000-2015; while farmland conversion for non-grain production uses accounted for 93.33% and 55.22% of the total farmland losses of the peri-urban and rural households, respectively. (3) The top considered factors in grain-production decision-making of the peri-urban and rural households were irrigation (55.32% versus
40.38%), grain-production cost (46.81% versus 53.85%), and grain-selling price (36.17% versus 36.54%). (4) The peri-urban households had an average rice deficit of -364kg while the rural households had a surplus of 312kg. (5) In both villages, two thirds of the surveyed farmers preferred rural living and around a half were willing to farm; while the ratios for their younger generation were one fifth and one tenth, respectively. Our findings suggest that UAFL could cause food self-insufficiency in the core areas of urbanization but often do not raise a legitimate concern on food security from local people, and that urban containment would not be effective for farmland preservation. We argue that UAFL can cause sustainability concerns other than food security and deserves place-based diagnoses of the real problems associated with UAFL in different contexts.

4.1 Introduction

Urbanization – which is often associated with modern industries, advanced technology, and better life quality – is a long-term, global trend (United Nations 2018). However, urbanization is also associated with many undesirable social-environmental consequences (Kates and Parris 2003), among which the worldwide farmland loss has been long attracting regional and global attention (Edgens and Staley 1999, Seto et al. 2000, Bren d’Amour et al. 2017). To promote urban development, or to preserve farmland resource, that seems the problem. Unfortunately, whether and how to protect farmland from urbanization has remained a decades-long policy debate among stakeholders such as farmers, the agri-food industry, urban developers, and land use managers (Fischel 1982, Edgens and Staley 1999, Azadi et al. 2012).

9 This chapter was written in collaboration with Rimjhim Aggarwal, and Ligang Lyu, and will be submitted for publication after final revisions.
The debate is rooted in two unsettled questions. First of all, is farmland loss a real problem? The main concern is on the consequent risk of insufficient food supply (Edgens and Staley 1999, Seto et al. 2000, Bren d’Amour et al. 2017). How to feed the drastically growing and rapidly urbanizing world population in the twenty-first century is widely recognized as a prime sustainability challenge (Godfray et al. 2010, United Nations 2015). FAO’s study suggests that 77% of the agricultural production growth during 1961-2005 could be attributed to higher yields, 14% to farmland expansion, and 9% to increases in cropping intensity (Alexandratos and Bruinsma 2012). Yet, advancement of agricultural technologies for further increasing grain yields is unpredictable. More practical options are to close yield gaps via better transferring available agricultural technologies (Foley et al. 2011, Mueller et al. 2012), to increase cropping intensity, or to cultivate new farmland. In fact, global farmland did increase during the last few decades, but the annual growth rate reduced from 0.24% during 1961-2010 to 0.04% in 1995-2010 (Ausubel et al. 2013). The farmland area of the United States already peaked in 1950 (Theobald 2001), and China around 2000 (Liu et al. 2014a, Ning et al. 2018). Synthesis of regional land change trends also shows a tendency that agricultural expansion of subsistence and small-scale farming gives way to agricultural intensification through time (Turner II 2001, DeFries et al. 2004, Mustard et al. 2004). Still, the halting of farmland expansion and the increasing farmland loss could be a cause, or instead, a result of the agricultural intensification (Rudel et al. 2009). In the case of being the result, farmland loss will not be a legitimate concern for food security.
Second, even if farmland preservation is a policy imperative, is the loss primarily caused by urbanization? Research interests are often in urban sprawl, with typically side attention to the consequent urban encroachment of farmland (Tan et al. 2005, Jiang et al. 2012, Pandey and Seto 2015, Bren d’Amour et al. 2017, Liu et al. 2019). Occasionally, data were documented for further assessing the contribution of urban uptake to total farmland loss. For example, Sleeter et al. (2013) reported that, of the ca. 90,000 km² farmland loss during 1973-2000 across the Conterminous United States, 34,400 km² (i.e., 38.22%) was converted to developed land. Liu et al. (2014a) found that 45.96% of the lost farmland in China went to urban built-up land during 1980s-2000, 55.40% during 2000-2010. A long-term study of the Europe’s land dynamics (Fuchs et al. 2015) demonstrated that only 8.22% of the lost farmland during 1900-2010 was converted to urban and rural settlements, 16.44% to forest, 71.23% to grassland (Table 3 therein). Increasingly, scholars are paying attention to the conversions of farmland for rural settlement expansion (Liu et al. 2010, Long and Li 2012), non-grain production uses (Su et al. 2014, Prokop 2018, Scheidel and Work 2018, Su et al. 2020), and farmland abandonment (Nguyen et al. 2018, Shi et al. 2018, Zou et al. 2018). Nonetheless, comprehensive research is rare that can depict the full picture of how urbanization directly and indirectly relates to farmland loss.

To build more consensus on whether/how to protect farmland from urbanization, there is a need for timely recognition of the multi-faceted and meta-coupling nature of urbanization (Seto et al. 2012, Acuto et al. 2018), as well as the place-variant complexity regarding the intertwined feedbacks between urbanization, farmland loss, and agri-food
production (Seto and Ramankutty 2016). In the sparsely populated United States – a major food exporter of the world, critics of farmland preservation see an anti-development overzeal rather than a food security challenge (Fischel 1982), and treat farmland loss as at most a “long-term and speculative rather than urgent” challenge (Gottlieb 2015). While in densely populated China – the world’s main food importer, farmland preservation is written into laws, requiring a national minimum of 1.8 billion mu (120 million ha) (Long et al. 2012). Azadi et al. (2012) contend that different societies have different concerns and land use priorities, thus the less developed, developing, and developed worlds should respond to UAFL differently. Indeed, Azadi et al. (2011) found that farmland loss was more intensified in developing countries where rapid economic growth and structural transition was going on, and influencing factors of UAFL differed in the three categories of countries. Even in a same country as China, the influencing factors of urban encroachment of farmland were found to differ between the county and provincial levels (Jiang et al. 2012). Also, the influencing factors of farmland loss to urban uptake differ from those driving farmland loss to abandonment (Shi et al. 2018). With all the complexity of UAFL, no wonder that existing farmland preservation policies have varying degrees of effectiveness (Alterman 1997), and in particular, were found largely ineffective in China (Lichtenberg and Ding 2008, Zhong et al. 2014).

In the above context, the present study aims to help close the knowledge gap on how different places of rural-urban systems couple with and differ from one another in terms of UAFL, which is expected to shed new lights on how to deal with the UAFL issue. To this end, below we propose an analytical framework from the core-periphery perspective
(Krugman 1980, 1991), which maps out the key feedbacks between the core and periphery areas of urbanization that cause four types of farmland loss and thus potentially food self-insufficiency (Figure 5.4). Underpinning the framework is the fact that urban core and the rural periphery have different social-environmental niches in the coupled rural-urban system, thus leading to multi-level, multi-dimensional, different manifestations of the UAFL issue in the two types of regions. Structured by the framework, diagnostic hypotheses can be made regarding the patterns, causes, and consequences of UAFL in the core and periphery areas; then correlated evidences can be collected on farmland loss of each type and related social-environmental components in the two settings to cross-validate the hypotheses. In what follows, Section 2 elaborates on the framework, and develops three interlinked falsifiable hypotheses; Section 3 introduces the materials and methods for falsifying the hypotheses in the context of China; Section 4 presents the macro-micro manifestations of UAFL in comparatively core and periphery areas of China; Section 5 discusses the implications for dealing with UAFL, and Section 6 concludes with our key argument and future research directions.

4.2 Analytical Framework and Diagnostic Hypotheses

As observed all over the world, a region can often be “differentiated into an industrialized ‘core’ and an agricultural ‘periphery’” (Krugman 1991). The Nobel Prize winning research by Krugman (1979, 1980, 1991) shows how the endogenous spatial differentiation becomes possible simply because industrial firms realize increasing returns to scale and minimize transport costs. Complementarily, the work by Yang (1990) shows that the differentiation of the urban core and the rural periphery can also
result from industrial firms’ having increasing returns to economies of specialization and minimizing transaction costs (which include transport costs). These theories imply that the rural and the urban are interacting parts of the same coupled system, with the economic dimension exhibiting industrial agglomeration, the population dimension exhibiting rural-to-urban migration, and the landscape dimension exhibiting urban encroachment of rural land uses. The loss of farmland – an often-dominating land use type of rural landscapes – is a landscape symptom of the multi-level, multi-dimensional, intertwined social-environmental processes that are captured in the broad concept of urbanization.

Unlike the simplification of a rural-urban dichotomy made in the economic theories for conveniences in mathematical analysis, our framework for analyzing UAFL (Figure 5.4) characterizes the rural and the urban as a social-environmental continuum. At the urban end of the rural-urban continuum, economic growth driven by increasing returns of whatever kinds consumes land as an input (Azadi et al. 2011), which feeds back to more economic growth (Bai et al. 2012). This self-reinforcing feedback loop causes direct urban encroachment of the rural landscape, which in densely populated areas has been intensively cultivated for farming. Thus, the rural landscape transformation is featured by the most widely studied type of farmland loss – farmland converted for urban development (Tan et al. 2005). Moving toward the rural end of the continuum, there are selective urban-to-rural capital flows, such as investments in commercial farming (Su et al. 2014, Su et al. 2020), and remittances from rural household members that work in the urban (Lambin et al. 2001, Davis and Lopez-Carr 2014), causing the second and third
types of farmland loss – farmland converted for non-grain production and for rural housing development. More remittances from the urban and less rural outmigration lead to increasing expansion of rural settlement at largely the cost of farmland (Liu et al. 2010, Long and Li 2012). The social-political context can make urban-to-rural capital flows selective in the sense that farmland conversions for non-grain production are often restricted, and that less competitive rural labors may fail to find a job in the urban due to being aged, lacking proper skillsets, or other reasons. At the rural end of the continuum, successful outmigration of rural labors, sometimes associated with their families, can cause labor shortage in grain production and consequently the fourth type of farmland loss – farmland fallow or abandonment in especially marginal areas (Nguyen et al. 2018, Shi et al. 2018, Zou et al. 2018).

The four types of UAFL all reduce the farmland area for grain production, though there are usually also conversions to farmland from other land uses, such as grassland, unused land, and forest. Increasingly, however, the gains of newly cultivated farmland would not be able to compensate the loss of farmland (Ausubel et al. 2013), especially high-quality farmland (Seto et al. 2000, Bren d’Amour et al. 2017). Once grain yield remains stable, the farmland under cultivation for grain production determines a region’s grain self-supply, which would be affected by UAFL. On the other side, the grain demand would increase, even with a stable total population – since urban population have more meat-intensive diets as compared to the rural (Tilman et al. 2011). The supply-demand deficits or surpluses can be resolved via interregional and global grain trade. The point is, food security is determined by complex social-environmental processes, and
whether UAFL becomes a policy imperative for ensuring food self-sufficiency should be considered in the broad context of the coupled rural-urban system.

**Figure 4.1** A diagnostic framework of multiple potential causal loops for understanding the patterns and processes of urbanization-associated farmland loss and the impact on grain self-sufficiency. “+” means positive impacts while “-” negative; “R” refers to a self-reinforcing feedback loop, while “B” means a balancing loop.

To test the structural validity of the proposed framework for understanding UAFL as a landscape syndrome of the coupled rural-urban system (Fig. 4.1), three interlinked diagnostic hypotheses are made here for empirical cross-validation: (1) Patterns – there are structural differences between the urban core and rural periphery areas regarding UAFL, with the urban core dominated by farmland conversions for urban development and non-grain production while the rural periphery dominated more by conversions for rural development and farmland fallow/abandonment. (2) Causes – the dominant types of UAFL in the urban core are caused by urban economic and population growth and selective urban-to-rural capital flows, while those in the rural periphery are caused by selective urban-to-rural capital flows and selective rural-to-urban population migration. (3) Consequences – with the differing causes, different social-environmental symptoms
would emerge in the core and periphery areas. In particular, UAFL can cause grain self-insufficiency in the urban core, but less likely in the rural periphery.

4.3 Materials and Methods

4.3.1. Land Use/Cover Data for Diagnosis of UAFL Patterns

We used the China Land Use/Cover Dataset (NLCD-China) from the Institute of Resources and Environment, Chinese Academy of Sciences, produced every five years for long-term monitoring of China’s resources and environment since the 1980s (Liu et al. 2002). These datasets have been widely-used for researching China’s land use/cover changes (Deng et al. 2015, Liu et al. 2015). NLCD-China are classified into six first-level classes: farmland, woodland, grassland, water body, built-up land, and unused land, with twenty-five second-level classes (Liu et al. 2005). The overall accuracy for the twenty-five sub-classes is above 91% (Liu et al. 2014a). For the structural analysis of farmland loss in this study, the sub-classes were reclassified into seven new classes (see Appendix B, Table S4.1 for the reclassification scheme): farmland; barely/sparsely vegetated land; moderately/densely vegetated land; water body; industrial, mining, and transportation land; rural settlement; and urban built-up land. The reclassified land use/cover types do not align perfectly with the proposed framework. For interpretation, the industrial, mining, and transportation land falls usually into the urban; agricultural land for non-grain production such as nursery plantation, vegetable production, pond farming/fishery, and duck rearing (Su et al. 2020) falls mostly into vegetated land or water body; while abandoned/fallow farmland falls into the barely/sparsely vegetated land.
Our focal time period is from 2000 to 2015, when China’s population urbanization level increased from 36.22% to 56.10%, and farmland suffered from a net decline of $1.51 \times 10^6$ hm$^2$ (Liu et al. 2014a, Ning et al. 2018). To compare the structural dynamics of farmland loss in the core and more periphery areas, we divided the NLCD-China datasets into two parts along China’s “geo-demographic demarcation line” (i.e., the red line in Fig. 4.2A), which is also known as the Hu Line or Heihe-Tengchong Line (Yue et al. 2003, Ge et al. 2018). The China core on the southeast side of the line covers 42.9% of the national area and 96% of the total population, while the China periphery on the northwest side of the line covers 57.1% of the area and only 4% of the population (Yue et al. 2003). Though, the population share of the China core continued to decrease, reaching 90.8% in 2000, due to rapid natural growth in the China periphery (Yue et al. 2003). Land use conversion matrix analysis was conducted for the China core and periphery separately using the land use/cover datasets in 2000, 2005, 2010, and 2015, to determine the structural dynamics of the farmland loss to the other six land use/cover types.
Figure 4.2 Study areas. (A) Jiangsu Province in eastern China; (B) Pukou District, a satellite city of the fast urbanizing Nanjing metropolis, Jiangsu Province; (C) Xianian Town at the western border of Pukou District for the local-scale study; and (D) Shanxi Village and Shili Village along a rural-urban gradient for the rural household interviews and surveys.

4.3.2. Field Survey for Diagnosis of UAFL Causes and Consequences

Aside from a minor portion of farmland utilized by governments specifically through state-owned agricultural companies, most of China’s farmland is owned collectively by villages – practically under the decision-making of rural households. At the macro level, UAFL is a result of rural households’ quitting farming in certain social-environmental contexts, either actively or passively. Thus, to understand farmers’ decision-making mechanisms and contexts regarding farmland use in the core and periphery areas, rural household surveys and supplementary village surveys were conducted from late May to early June 2017 in two contrasting villages. Firstly, the Nanjing metropolis of Jiangsu province, China (Figs. 4.2A-B) was selected for the fast urbanization it has gone through and also for research convenience. Then, the sampling area was narrowed down to Xingdian Town, Pukou District in west Nanjing (Figs. 4.2B-C), for its being one of the
main farmland preservation zones of Nanjing. Xingdian Town is mostly alluvial plain
(Fig. 4.2D), with 141 km² land, 50.4 thousand population and 14 composing villages.
For the interviews and surveys, Shanxi Village was randomly selected from seven
comparatively remote rural villages, Shili Village was randomly selected from the seven
more per-urban ones.

A village survey questionnaire was used to collect information on village area,
demographics, labor, and major enterprises by interviewing cadres of the villager
committee. The household questionnaire was used to collect information on grain
production and consumption, farmland endowment and utilization, willingness to rent in
and rent out farmland, the intentions of its different generations to emigrate and to farm,
and self-evaluated life-satisfaction, as well as a wide variety of household socioeconomic
characteristics. A total of 55 household surveys were conducted in each village by
interviewing the household head in most cases, or with other household members when
the head was absent. The households were picked up randomly while interviewers from
a local university (i.e., Nanjing University of Finance and Economics) were walking in
the selected villages during daytime; all interviews were conducted in Mandarin, with
each lasting one hour or longer. After excluding incomplete questionnaires, there were
47 effective household surveys for Shili Village and 52 for Shanxi Village, with
additional notes. Then, descriptive statistics on UAFL related social-environmental
variables were derived for comparison between the rural and per-urban villages with R.
This comparative case study methodology is common in social sciences (Liu et al.)
2014c), and is believed to be especially useful in understanding the motivational aspect of land use/cover changes (Yu et al. 2018).

4.4 Results

4.4.1. Farmland Loss Patterns in Core and Periphery areas of China

For the whole China (Fig. 4.3A), the national farmland loss from 2000 to 2015 was increasingly dominated by development of urban built-up, rural settlement, and industry, mining, or transportation. The ratio of development uptake increased from 47.30% in 2000-2005 to 62.43% in 2005-2010 and to 77.44% in 2010-2015. The contribution of industrial, mining, and transportation land to farmland loss elevated from 9.59% in 2000-2005 to 19.18% in 2005-2010 and to 36.85% in 2010-2015. The ratio of rural development’s uptake of farmland increased slightly from 13.56% in 2000-2005 to 14.70% in 2005-2010 and to 15.85% in 2010-2015. Contrastingly, the proportion of urban encroachment of farmland remained stably around 25%.
Figure 4.3 Structural dynamics of farmland loss to other land uses in 2000-2015, for (A) the whole China, (B) the ‘core’ of China – areas on the southeast side of the Heihe-Tengchong line (Figure 2A), and (C) the ‘periphery’ of China – areas on the northwest side of the Heihe-Tengchong line.

For the China core (Fig. 4.3B), its farmland loss pattern was similar to that of the whole China. Most of the loss could be increasingly attributed to conversions for development, which accounted for 56.93%, 66.98%, and 82.12% in 2000-2005, 2005-2010, and 2010-2015, respectively. Also, the contribution of industrial, mining, and transportation land to farmland loss elevated from 11.74% in 2000-2005 to 20.47% in 2005-2010 and to 40.96% in 2010-2015. The ratio of rural development’s uptake of farmland remained quite stably below 16%, while urban development’s contribution dropped from around 30% in 2000-2005 and 2005-2010 to 24.90% in 2010-2015.

For the China periphery (Fig. 4.3C), its farmland loss pattern differed notably from the patterns of the whole China and China core. The majority of farmland loss went to vegetated lands and water body, which accounted for 90.61%, 84.08%, and 45.69% in 2000-2005, 2005-2010, and 2010-2015, respectively. Yet, farmland conversions for
development – including industrial, mining, and transportation construction, rural
development, and urban built-up – all increased rapidly especially since 2010. In
particular, urban development’s contribution elevated from 4.50% in 2000-2005 to 7.32%
in 2005-2010 and to 24.38% in 2010-2015.

4.4.2. Farmland Loss Causes and Consequences in Frontier and Periphery of
Urbanization

4.4.2.1. Different social-environmental contexts of the peri-urban and rural villages

Based on the survey respondents’ self-reported travel time (Table 4.1), the rural village
(i.e., Shanxi Village) is indeed more periphery than the peri-urban village (i.e., Shili
Village), confirming the effectiveness of our villages sampling. The average travel time to
the local urban center (i.e., Xingdian Town Downtown) from the peri-urban village was
about half that from the rural village (12 ± 10 versus 23 ± 15 min), while the average travel
time to the regional urban center (i.e., Pukou District Downtown) was less contrasting, 56
± 18 min and 70 ± 28 min from the peri-urban village and the rural village, respectively.
The rural village was self-subsistence agricultural economy, while the peri-urban village
had three enterprises as part of the market economy that provided local farmers with off-
farm job opportunities. The per-urban and rural villages had similar proportions of
villagers over 60 years old (20.64% versus 21.73%), and similar labor ratios (50.52%
versus 53.51%). Yet, the more periphery rural village had a much higher population
density (356 person/km²) than the peri-urban village (262 person/km²).
Table 4.1
Characteristics of the two sampled villages: peri-urban versus rural#

<table>
<thead>
<tr>
<th></th>
<th>Shili Village</th>
<th>Shanxi Village</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time traveling to Xingdian Town Downtown (min)</td>
<td>12 ± 10</td>
<td>23 ± 15</td>
</tr>
<tr>
<td>Time traveling to Pukou District Downtown (min)</td>
<td>56 ± 18</td>
<td>70 ± 28</td>
</tr>
<tr>
<td>Number of major enterprises in the village</td>
<td>3*</td>
<td>0</td>
</tr>
<tr>
<td>Area (km²)</td>
<td>12.2</td>
<td>6.2</td>
</tr>
<tr>
<td>Population</td>
<td>3197</td>
<td>2209</td>
</tr>
<tr>
<td>Number of villagers over 60 years old</td>
<td>660</td>
<td>480</td>
</tr>
<tr>
<td>Number of workers</td>
<td>1615</td>
<td>1182</td>
</tr>
</tbody>
</table>

# Of the three enterprises in Shili Village, one is in the business of manufacturing and selling metals, plastic and chemical products, and daily necessities; one manufactures cable accessories; and the third produces local tea.

4.4.2.2. Rural households’ characteristics, farmland use, and grain production decision-making

Consistent with official demographic data from the village surveys (Table 4.2 versus Table 4.1), the peri-urban households had a lower worker ratio than the rural village (59.62% versus 67.50%, p < 0.05), though both were higher than the officially reported numbers (50.52% and 53.51%). Of the household worker, the proportions of grain-growing worker, agricultural worker, and urban worker—either part-time or full-time—were 3.23%, 45.16%, and 61.29% respectively for the peri-urban households, while 40.74%, 48.15%, and 44.44% respectively for the rural households. These differences were statistically significant for the grain-growing worker proportion and urban worker proportion, yet insignificant for agricultural worker. Further, the peri-urban households and rural households had about the same amount of farmland (7.5 ± 7.0 versus 6.7 ± 4.0 mu, p > 0.05). Of all the farmland, much less was cultivated for grain production by the peri-urban households than by the rural (6.67% versus 44.77%, p < 0.05), while no statistical significance (p > 0.05) was detected between the peri-urban and rural households for farmland area left fallow, percentage of households converted farmland
for housing in 2000-2015, percentage converting farmland for non-grain production, and percentage lost farmland to urban development. Besides, similar for both the peri-urban and rural households, only less than 10% wished to rent in more farmland; while 46.81% peri-urban and 76.47% rural households wished to rent out farmland ($p < 0.005$).

Table 4.2

<table>
<thead>
<tr>
<th>Characteristics and farmland use of the peri-urban and rural households#</th>
<th>Shili Village</th>
<th>Shanxi Village</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Household size</td>
<td>5.2 ± 3.2</td>
<td>4.0 ± 2.1</td>
</tr>
<tr>
<td>Number of workers</td>
<td>3.1 ± 2.3</td>
<td>2.7 ± 1.8</td>
</tr>
<tr>
<td>***Number of grain-growing worker (part-time and full-time)</td>
<td>0.2 ± 0.5</td>
<td>1.1 ± 0.9</td>
</tr>
<tr>
<td>Number of agricultural worker (part-time and full-time)</td>
<td>1.4 ± 2.0</td>
<td>1.3 ± 0.8</td>
</tr>
<tr>
<td>*Number of urban worker (part-time and full-time)</td>
<td>1.9 ± 1.8</td>
<td>1.2 ± 1.3</td>
</tr>
<tr>
<td>Area of farmland (mu)</td>
<td>7.5 ± 7.0</td>
<td>6.7 ± 4.0</td>
</tr>
<tr>
<td>*Area of farmland for grain/rice production</td>
<td>0.5 ± 1.6</td>
<td>3.0 ± 3.6</td>
</tr>
<tr>
<td>Area of fallow farmland (mu)</td>
<td>0.7 ± 2.8</td>
<td>0.3 ± 0.9</td>
</tr>
<tr>
<td>Percentage of households converted farmland for housing in 2000-2015</td>
<td>29.79%</td>
<td>36.54%</td>
</tr>
<tr>
<td>Percentage of households converted farmland for non-grain production</td>
<td>82.99%</td>
<td>63.46%</td>
</tr>
<tr>
<td>Percentage of households lost farmland to urban development</td>
<td>14.89%</td>
<td>1.92%</td>
</tr>
<tr>
<td>Percentage of households wishing to rent in farmland</td>
<td>8.51%</td>
<td>9.80%</td>
</tr>
<tr>
<td>***Percentage of households wishing to rent out farmland</td>
<td>46.81%</td>
<td>76.47%</td>
</tr>
</tbody>
</table>

# 1. *, **, and *** stand for the respective statistical significance levels at $p < 0.05$, $p < 0.01$, and $p < 0.005$ (same hereafter). The unit of $mu$ is widely used in China, and 1 $mu$ equals to 0.067 $hm^2$. 2. Rice is the dominant grain in the surveyed area, while only one of the 99 surveyed households cultivated winter wheat and eight cultivated corn.

Consistent with the small proportions of farmland cultivated for grain production (Table 4.2), farmland area was only a marginal factor considered in farmers’ grain-production decision-making (Table 4.3). The top three concerns in grain production of the peri-urban and rural households were irrigation (55.32% versus 40.38%), grain-production costs (46.81% versus 53.85), and grain-selling price (36.17% versus 36.54%). The other surveyed factors including difficulty in buying grain, grain-production subsidy, farming-leisure tradeoffs, difficulty in selling grain, farmland area and quality were identified as influencing factors by no more than one fourth surveyed households in both villages. The peri-urban and rural households complained about four factors that made
grain-production unfeasible, including nursery stock cultivation (14.89% versus 5.77%), labor shortage in grain-production due to household duties (12.77% versus 3.85%), and limited grain-production skills of the younger generation (4.26% versus 15.38%). No statistical significance was detected between the peri-urban and rural households for importance of each factor influencing their grain-production decision.

### Table 4.3
Factors influencing the grain-production decision of the peri-urban and rural households

<table>
<thead>
<tr>
<th>Factors considered in grain-production decisions</th>
<th>Shili Village</th>
<th>Shanxi Village</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation</td>
<td>55.32%</td>
<td>40.38%</td>
</tr>
<tr>
<td>Grain-production costs</td>
<td>46.81%</td>
<td>53.85%</td>
</tr>
<tr>
<td>Grain-selling price</td>
<td>36.17%</td>
<td>36.54%</td>
</tr>
<tr>
<td>Difficulty in buying grain</td>
<td>19.15%</td>
<td>21.15%</td>
</tr>
<tr>
<td>Grain-production subsidy</td>
<td>12.77%</td>
<td>13.46%</td>
</tr>
<tr>
<td>Farming-leisure trade-offs</td>
<td>14.90%</td>
<td>1.92%</td>
</tr>
<tr>
<td>Difficulty of selling grain</td>
<td>10.64%</td>
<td>23.08%</td>
</tr>
<tr>
<td>Farmland area</td>
<td>10.64%</td>
<td>19.23%</td>
</tr>
<tr>
<td>Farmland quality</td>
<td>10.64%</td>
<td>7.69%</td>
</tr>
<tr>
<td>Other factors that made grain-production unfeasible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nursery stock cultivation</td>
<td>14.89%</td>
<td>5.77%</td>
</tr>
<tr>
<td>Labor shortage in grain-production due to household duties</td>
<td>12.77%</td>
<td>3.85%</td>
</tr>
<tr>
<td>Limited grain-production skills of the younger generation</td>
<td>4.26%</td>
<td>15.38%</td>
</tr>
</tbody>
</table>

# 1. Based on responses from the surveyed farmers, the grain-production subsidy was based on farmland area instead of the actual grain-production area or output. 2. No statistically significant difference was detected between the peri-urban and rural.

#### 4.4.2.3. Rural households’ grain self-sufficiency, migration/farming tendency, and life-satisfaction

Consistent with the finding that peri-urban households cultivated less farmland for grain production (Table 4.2), the annual average rice output of the peri-urban households was much less than that of their rural counterparts (180 versus 899 kg, \( p < 0.005 \)) (Table 4.4). Though the peri-urban households had a larger size (Table 4.2), they consumed similar amount of rice at home as the rural (544 ± 420 versus 587 ± 376 kg, \( p > 0.05 \)). As a result of rice production differences, the peri-urban households had an annual rice
deficit of -364 ± 665 kg, while the rural households had a surplus of 312 ± 1173 kg.

Around half of the respondents were willing to farm for both the peri-urban and rural households (52.17% versus 43.14%, \( p > 0.05 \)). Only about one tenth of their younger generations were willing to farm, with no statistical significance between the two household types.

**Table 4.4**
Grain self-sufficiency, migration/farming tendency, and life-satisfaction of the peri-urban and rural households

<table>
<thead>
<tr>
<th>Characteristics of the survey respondents</th>
<th>Shili Village</th>
<th>Shanxi Village</th>
</tr>
</thead>
<tbody>
<tr>
<td>***Rice production per household (kg)</td>
<td>180 ± 555</td>
<td>899 ± 1263</td>
</tr>
<tr>
<td>Rice consumption (at home) per household (kg)</td>
<td>544 ± 420</td>
<td>587 ± 376</td>
</tr>
<tr>
<td>***Rice surplus/deficit per household (kg)</td>
<td>-364 ± 665</td>
<td>312 ± 1173</td>
</tr>
<tr>
<td>Percentage of respondents who are willing to farm</td>
<td>52.17%</td>
<td>43.14%</td>
</tr>
<tr>
<td>Percentage of respondents whose younger generations are willing to farm</td>
<td>10.64%</td>
<td>13.73%</td>
</tr>
<tr>
<td>Respondent’ life-satisfaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage of very unsatisfied</td>
<td>2.13%</td>
<td>1.92%</td>
</tr>
<tr>
<td>Percentage of unsatisfied</td>
<td>4.26%</td>
<td>9.62%</td>
</tr>
<tr>
<td>Percentage of neutral</td>
<td>55.32%</td>
<td>48.08%</td>
</tr>
<tr>
<td>Percentage of satisfied</td>
<td>21.28%</td>
<td>36.54%</td>
</tr>
<tr>
<td>Percentage of very satisfied</td>
<td>17.02%</td>
<td>3.85%</td>
</tr>
<tr>
<td>Percentage of respondents who prefer rural living</td>
<td>68.09%</td>
<td>68.63%</td>
</tr>
<tr>
<td>Percentage of respondents whose younger generations prefer rural living</td>
<td>17.02%</td>
<td>21.57%</td>
</tr>
<tr>
<td><strong>Percentage of households that bought urban house(s) in 2000-2015</strong></td>
<td>31.91%</td>
<td>13.46%</td>
</tr>
</tbody>
</table>

#1. The amount of rice produced per household was originally reported in terms of unhulled rice, which was then converted to rice with a milled rice rate of 72% as told by interviewed farmers.

Overall, the peri-urban and rural respondents had similar levels of life-satisfaction \( (p > 0.05) \) (Table 4.4). The proportions of being very unsatisfied, unsatisfied, neutral, satisfied, and very satisfied were 2.13%, 4.26%, 55.32%, 21.28%, and 17.02% respectively for the peri-urban respondents, and contrastingly, were 1.92%, 9.62%, 48.08%, 36.54%, and 3.85% respectively for the rural respondents. Two thirds of respondents in both villages expressed preference of rural living over urban living, yet it applied to only one fifth of their younger generation (with no statistical significance
between two household types). Yet, 31.91% of the peri-urban households and 13.46% of the rural bought one or more housing units in the urban during 2000-2015 ($p < 0.01$).

4.5 Discussion

Farmland loss has been common in urbanizing areas across the world, resulting in a decades-long policy debate in many countries regarding whether/how to protect farmland during urbanization (Section 4.1). Farmland preservationists typically frame the issue as a problem of food insecurity due to urban encroachment of farmland, especially high-quality farmland (Tan et al. 2005, Jiang et al. 2012, Pandey and Seto 2015, Bren d’Amour et al. 2017, Liu et al. 2019). However, opponents doubt if farmland loss would actually cause food insecurity and whether urban development is responsible for farmland loss (Fischel 1982, Edgens and Staley 1999, Gottlieb 2015). We proposed an analytical framework to illustrate how this UAFL issue is place-based, depending on a focal region’s social-environmental niche in the coupled rural-urban system (Section 4.2).

To test the structural validity of our framework, we did a comparative study of the patterns, causes, and consequences of farmland loss in the core and periphery areas of urbanization in the context of China (Section 4.4).

Our survey has shown that only around 20% of both the peri-urban and rural households considered any difficulty of buying grain in making their farming decisions (Table 4.3). Yet, we found that, while the rural periphery households had a rice surplus of 312kg, the peri-urban households had indeed a rice deficit of -364kg (Table 4.4). With on average a larger household size (Table 4.2), the peri-urban households actually consumed similar amount of rice at home as their rural counterparts. Yet, they produced
much less rice than the surveyed rural households (Table 4.4). The less rice production of the peri-urban households was not due to their lack of farmland, but their devoting much less labor and farmland to rice production (Table 4.2). In fact, lack of (good) farmland was reported as only a marginal factor in the farming decision-making of both the peri-urban and rural households (Table 4.3). These findings show that, though decreasing rice production is responsible for the increasing rice self-insufficiency along with urbanization, economic viability (including accessibility to irrigation) instead of farmland loss is to blame for the decreasing rice production.

Our analysis of the structural patterns of farmland loss dynamics in the core and periphery areas of China has shown that the most studied urban encroachment of farmland is only part of the farmland loss story (Figure 5.7). Specifically, the ratio of farmland loss to urban encroachment remained below one third in the southeast urban China during 2000-2015, and increased in the northwest rural China from below one tenth before 2010 to about one fourth thereafter. However, over half of the farmland loss could be attributed to the consumption by development – which in our land use/cover classification scheme includes urban development, rural development, and other development uses such as industrial, mining, and transportation construction – and the ratio had increased over time in both the China core and periphery. In this regard, special attention should be given to the land use/cover classification schemes used in relevant studies. They often use “built-up land,” “impervious land,” or “settlement” instead of “urban” (Sleeter et al. 2013, Fuchs et al. 2015, Pandey and Seto 2015), which is essentially “development lands” in our case with subtypes driven by different social-
environmental processes of urbanization. Thus, the top to blame for farmland loss is not urban sprawl, but the expansion of development lands.

We disaggregated farmland loss into four subtypes that relate to urban economic and population growth, selective urban-to-rural capital flows, and/or selective rural-to-urban population migration (Figure 5.4). The four types of farmland loss – fallow/abandonment, or converted for rural development, non-grain production, or urban development – are all associated with urbanization, albeit through different social-environmental pathways in the core and periphery areas of urbanization (Figure 5.4). The different pathways underlying different farmland loss patterns would give rise to different associated social-environmental symptoms. For example, due to the elder generation’s disadvantages in competing for urban jobs, a social symptom of UAFL is widely reported in relatively periphery areas – rural hollowing (Liu et al. 2010, Liu et al. 2014b). Our survey also shows that urban areas are attracting the younger generation while rural areas are having an aging labor. Moreover, the emerging phenomenon of cash crop plantation has been documented in the frontiers of urbanization (Su et al. 2014, Prokop 2018, Scheidel and Work 2018, Su et al. 2020), which may cause the “green grabbing” problem (Scheidel and Work 2018). In the surveyed peri-urban village, nursery farming partially replaced grain-production, which caused irrigation unavailability to grain-production farmers. Thus, even when food security is not a concern, other sustainability challenges associated with UAFL also deserve policy attention.
So, should we contain urban development to protect farmland for maintaining food security? Well, as discussed above, to promote urban development, or to preserve farmland resource, that is not the problem – at least not the whole problem. For instance, preserving farmland in the periphery areas of urbanization would be anti-developmental, where increasing human well-being and tackling rural aging would be a higher priority. Contrastingly, allowing urban sprawl to encroach farmland in the core areas of urbanization may indeed cause food self-insufficiency, which in times of climate extremes or trade wars would threaten local food security. Yet, a solution alternative to urban containment may be to promote grain storage at the household level, for say, one year. Moreover, existing farmland policies are implemented typically at the regional or national levels (Alterman 1997), often by exclusive zoning. This deprives the development right of the farmland preservation zones in the periphery, calling for policy attention to the social justice of farmland preservation. The point is, we need to go beyond the popular yet narrow framing that farmland loss due to urban sprawl would cause food insecurity. Instead, the farmland loss issue may be reframed as an urbanization-associated “landscape unsustainability syndrome” (Zhou et al. 2019). This syndrome-based framing explicitly recognizes the different archetypes (Oberlack et al. 2019) of UAFL in terms of farmland loss patterns, underlying causes, and associated consequences. In so doing, the UAFL issue will not be limited to urban sprawl and food security, but can be put on the broad sustainability agenda focusing on adaptive policymaking to address place-variant concerns associated with the long-term global trend of urbanization (Kates and Parris 2003).
4.6 Conclusion

Driven by the worldwide decades-long policy debate on whether/how to protect farmland during urbanization, this study has delved into the place-based nature of the UAFL issue. An analytical framework was proposed from a core-periphery systems perspective to illustrate how the patterns, causes, and consequences of UAFL differ among different places due to their different social-environmental niches in the coupled rural-urban system. Correlated evidences were collected on the structural patterns of farmland loss dynamics in the southeast versus northwest China during 2000-2015, and on causes and consequences of farmland loss in peri-urban and rural periphery villages by field survey in 2016. We found that, though decreasing rice production is responsible for the increasing rice self-insufficiency along with urbanization, farmland loss is not to blame for the decreasing rice production and urban encroachment is not always the top to blame for farmland loss. These findings suggest the inappropriateness of the causal attribution embedded in the popular framing that urban encroachment of farmland threatens food security. We conclude that, though UAFL could substantially reduce food self-sufficiency in the frontier of urbanization, food security is not a legitimate concern for farmland preservation, and that protecting farmland by urban containment would be ineffective. Our findings highlight four types of UAFL along the rural-urban continuum – farmland fallow/abandonment, farmland converted for rural development, farmland converted for non-grain production, and farmland converted for urban development – each with different social-environmental causal pathways of urbanization and with associated sustainability challenges more than just food self-insufficiency. Therefore, we
argue for reframing the farmland loss issue as an urbanization-associated “landscape unsustainability syndrome.” In so doing, policies other than urban containment for addressing food security become possible, and urbanization associated challenges other than farmland loss get deserved policy attention. For future research, the syndrome-based, diagnostic approach (Chapters 1 and 3) to addressing landscape unsustainability issues like UAFL can be advanced by examining in-depth the different archetypes of a landscape unsustainability syndrome. Extensive case studies are needed to document each archetype’s major unsustainability challenge, associated symptoms and key pathogenic feedback loops, as well as policy prescriptions and potential side effects. With sufficient case studies, further advances are possible by meta-synthesis and subsequently mechanistic modeling, for producing generalizable and actionable knowledge urgently needed for our common journey of sustainability.
CHAPTER 5
UNDERSTANDING TEMPORAL FEATURES OF FARMLAND LOSS IN DRASTICALLY URBANIZING CORE-PERIPHERY SYSTEM: A LANDSCAPE SUSTAINABILITY PERSPECTIVE

Abstract

As an emerging field, landscape sustainability science contributes to sustainability by addressing “what to develop versus what to sustain” through the landscape lens. Yet, few studies have applied the landscape sustainability perspective to address a widespread concern – farmland loss associated with the long-term, global trend of urbanization – on which existing findings are contradictory and policies are controversial, due to often a narrow focus on farmland loss to urban sprawl. The present study aims to examine the changing landscape features of urbanization-associated farmland loss (UAFL) in the core and periphery areas of Tongling City in eastern China during 2000-2015, and understand what shaped the temporal patterns and abnormalities, if any. We comparatively analyzed the temporal changes in farmland loss structure and pattern as well as land use/cover structure and conversions using 30m-grid land use/cover data in 2000, 2005, 2010, and 2015, and identified probable regime shifts in the socioeconomic and agrifood dynamics by changepoint detection using relevant data in 2000-2015 from various sources.

Considerable, increasing amount of farmland loss occurred in the core and periphery of Tongling during 2000-2015, when its population urbanization level increased from 57.43% to 79.41%. Urban encroachment of farmland accounted for 14.72%-74.36% of total farmland loss, with the ratio changing remarkably through time. Besides, farmland
became smaller in patch size, less regular in patch shape, and more isolated between patches, with the core becoming spatially more homogeneous while the periphery more heterogeneous. For changes of the whole landscape, land gains were persistently dominated by expansion of developed lands (including urban built-up land, rural settlement, and industrial, mining and transportation land), while all land use/cover types experienced the most intensive loss in 2010-2015 and in particular, the loss intensity of natural lands and farmland increased over time. Farmland loss area accounted for 8%-77% of total land use conversion, with the ratio generally decreasing during 2000-2015. Land use conversion structures of the core and the periphery differed except in 2005-2010, when probable regime shifts were detected in their socioeconomic and agrifood dynamics. The findings reveal a set of temporal features of landscape changes related to UAFL – some consistent between the core and periphery areas while others differ because of socioeconomic variations and land institutional coupling – which sheds new light on rethinking farmland preservation policymaking. Our research also highlights a big data gap for advancing the problem-driven diagnostic landscape sustainability research.

5.1 Introduction

With over three decades’ sustainability studies by landscape scientists, a converging field has been rapidly growing during the past fifteen years, with knowledge bases in landscape ecology, ecological economics, and sustainability science (Zhou et al. 2019). This emerging field, the so-called landscape sustainability science (Wu 2013b),

---

10 This chapter will be revised and later submitted for publication.
contributes to sustainability by addressing the meta-issue of “what to develop versus what to sustain” (Kates et al. 2005) through the lens of the landscape. This landscape sustainability perspective provides an unique entry to study sustainability issues – landscape pattern of human-environment interactions (Wu 2006, Turner 2010, Opdam et al. 2018). To date, progress has been made to provide spatially explicit landscape-based solutions to enhance eco-environmental sustainability of human-environment systems (Opdam et al. 2006, Liu et al. 2020). Increasingly, these practical studies are embracing sustainability’s sociocultural (Nassauer and Opdam 2008, Musacchio 2011, Wu 2019) and theoretical (Musacchio 2009b, Wu 2013b, Opdam 2018) dimensions. Yet, despite the notable efforts in “linking knowledge to action,” existing landscape sustainability studies have paid insufficient attention to “understanding human-environment interactions” (Zhou et al. 2019).

From the landscape sustainability perspective, landscape pattern provides “X-rays” of human-environment systems, giving hints on the underlying human-environment interactions that have sustainability implications (Zhou et al. 2019). For example, urbanization as a long-term global trend of human-environment interactions has been widely found to associate with the landscape change of urban expansion at the cost of farmland loss, which has raised regional to global concerns on food sustainability (Seto et al. 2000, Pandey and Seto 2015, Bren d’Amour et al. 2017). Existing studies tend to take urban sprawl as the problem entry, which limits research focus on how urban encroachment of farmland affects food production potential (Bren d’Amour et al. 2017, He et al. 2017). But, urban land only occupies about 0.5% of the Earth’s total land area,
with the ratio varying between 0.01%-10% at the country scale (Zhou et al. 2015). Furthermore, urban expansion’s contribution to total farmland loss also varies wildly depending on the study period and area (Sleeter et al. 2013, Liu et al. 2014a, Fuchs et al. 2015). No wonder that urban containment and farmland preservation policies have long been very controversial (Alterman 1997, Edgens and Staley 1999, Gottlieb 2015), because a major knowledge gap remains regarding the general spatiotemporal patterns of urbanization-associated farmland loss (UAFL), if any. To close this gap, a landscape sustainability perspective helps in raising three research questions that are broader than the existing framing. (1) What are the landscape features of UAFL and how do the features change over time? (2) What are the underlying human-environment interactions that give rise to these features? (3) What are the implications of these human-environment interactions for sustainability, economically, socially, and eco-environmentally?

Although the UAFL issue has a big stake, and as a typical manifestation of the sustainability meta-issue of “what to develop versus what to sustain,” is of fundamental relevance to landscape sustainability science, few studies have so far taken the landscape sustainability perspective to address UAFL. Answering the above questions is methodologically possible, given proper data. The primary aim of this study is to answer the first question, by examining the changing landscape features of UAFL during 2000-2015 in rapidly urbanizing Tongling City of eastern China, so to find any general temporal trends and abnormalities. The second and third questions are to be discussed in the context of relevant socioeconomic and agrifood dynamics in the study area. A
nuance of the study area is its core-periphery monocentric spatial structure (Figure 5.4), which provides twofold benefits. One is to cross-validate any generalization of findings by comparative studies, and the other is to explore how human-environment couplings between developed and developing areas shape UAFL. The latter, in particular, is of theoretical significance for landscape sustainability science in its potential to shed lights on how landscape sustainability may bridge local and regional/global sustainability (Wu 2012, Levin 2015), in the present case of implementing farmland preservation as collective action for public food security (Chien 2015, Wang et al. 2020).

5.2 Materials and Methods

5.2.1. Study Area

Tongling is a relatively young city (cf. a city in China corresponds to a county in the USA, in terms of its administrative level) of Anhui province in eastern China (Figs. 5.1A&B). The predecessor of Tongling was a major copper mining factory of China established in 1950, which gradually grew into a mining town that was officially established in 1952. The town later expanded to a small county (i.e., Tongguanshan District, corresponds to a city in the USA, like Tempe, Arizona) established in 1956, which laid the foundation of Tongling City Proper today. The mining county, Tongguanshan District, continued annexing, losing, and annexing the surrounding Tongling County from 1958 to 1971, when Tongling was formally established as a city composed of Tongling City Proper and Tongling County. Known today as “China’s copper capital,” Tongling had been the smallest city in China (1113 km²) until October 2015, when it annexed Zongyong County and expanded to 3008 km² (cf., Santa Cruz
County, Arizona, of 3206 km$^2$). This study focuses on the pre-annexation Tongling during 2000-2015, i.e., covering only Tongling City Proper (214.10 km$^2$) and the surrounding Tongling county (812.88 km$^2$) – the core and the periphery, respectively (Fig. 1C).

**Figure 5.4** Location and elevation of study area. (A) Anhui Province in eastern China; (B) Tongling City along the Yangtze River in south Anhui Province, with Zongyong County annexed in October 2015; (C) Elevation of the study area – the pre-annexation monocentric system – including the 20% core Tongling City Proper (214.10 km$^2$) and the 80% periphery Tongling County (812.88 km$^2$).

Tongling is a rare, ideal place for our empirical study because of three reasons. Firstly, it has a monocentric structure, with 20% area as the core surrounded by 80% the more periphery area. This sociopolitical setting provides the twofold research benefits highlighted in Introduction as a core-periphery system, with socioeconomic data of the naturally formed two parts that are rarely available. Secondly, Tongling is bounded in its west, northwest and north by the Yangtze River, and in the southeast, bounded by mountains (Fig. 5.1C). This rare biophysical setting minimizes the influences of urban centers in adjacent areas on Tongling’s landscape transformation. Thirdly, Tongling had undergone rapid urbanization during 2000-2015, with its population urbanization ratio increased from 57.43% (cf. that of China
was 56.1% in 2015) to 79.41% (cf. the urbanization level in developed countries like the USA is around 80%) (Tongling Statistical Bureau 2016). This allows our study to potentially provide prognostic implications for China and other areas with a big urbanization potential ahead.

5.2.2. Land Use/Cover Change and Landscape Pattern Analyses

The land use/cover data of the study area in 2000, 2005, 2010, and 2015 were from the China Land Use/Cover Dataset (NLCD-China) produced by Institute of Resources and Environment, Chinese Academy of Sciences, with a resolution of 30m (Liu et al. 2002). The datasets have been widely used for studying China’s land use/cover changes (Deng et al. 2015, Liu et al. 2015). There are six first-level classes in NLCD-China, including farmland, woodland, grassland, water body, built-up land, and unused land, and twenty-five sub-classes with their overall accuracy above 91% (Liu et al. 2005, Liu et al. 2014a). Our study highlights the sub-classes of built-up land (i.e., urban built-up land, rural settlement, and industrial, mining and transportation land) that are associated with different socioeconomic activities, and regroups the sub-classes of natural lands (i.e., woodland, grassland, water body, and unused land) into sparsely/barely vegetated land, densely/ moderately vegetated land, and water body that differs in their relative capacities in provisioning ecosystem services (Costanza et al. 1997). Thus, our reclassified data include the above six land use/cover types and farmland (see Appendix B, Table S4.1 for the reclassification scheme).

Followingly, based on ArcGIS 10.2, the spatial distribution of farmland loss to the other six land use/cover types in each study period was identified using “Raster
Calculator” and the loss structure was calculated by land conversion matrix analysis using “Tabulate Area.” Further, based on the R-package ‘landscapemetrics’ (Hesselbarth et al. 2019), farmland patches’ characteristics in terms of area, shape, and adjacency were quantified using six landscape metrics, i.e., Patch Size (mean), Patch Size (CV, coefficient of variation), Fractal Dimension Index (mean), Fractal Dimension Index (CV), Patch Density, and Aggregation Index (McGarigal et al. 2012, Riitters 2019).

Increase in mean patch size indicates the change tendency from smallholder farming toward scale farming; increase in mean patch fractal dimension (or shape complexity in general) indicates decreasing human modification, a proxy for agricultural intensification; increase in patch density and decrease in aggregation index cross-validate the increasing isolation and fragmentation of farmland patches; and CV indicates spatial heterogeneity.

Urbanization is usually associated with net farmland loss but not necessarily the regime shift from smallholder farming to scale farming, so we expect farmland to become smaller in patch size, less regular in patch shape, and more isolated between patches (Table 5.5).

**Table 5.5**
Landscape metrics for quantifying farmland pattern and hypothesized changes during urbanization.

<table>
<thead>
<tr>
<th>Category</th>
<th>Metrics</th>
<th>Unit</th>
<th>Range</th>
<th>Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>Patch Size (mean)</td>
<td>m²</td>
<td>0 or larger</td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>Patch Size (CV)</td>
<td>Percent</td>
<td>0 or larger</td>
<td>↑ or ↓</td>
</tr>
<tr>
<td>Shape</td>
<td>Fractal Dimension Index (mean)</td>
<td>None</td>
<td>[1, 2], the larger the less regular</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>Fractal Dimension Index (CV)</td>
<td>Percent</td>
<td>0 or larger</td>
<td>↑ or ↓</td>
</tr>
<tr>
<td>Adjacency</td>
<td>Patch Density</td>
<td>Number/m²</td>
<td>0 or larger, constrained by cell size</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>Aggregation Index</td>
<td>None</td>
<td>[0, 100], 100 is maximally aggregated</td>
<td>↓</td>
</tr>
</tbody>
</table>
To understand farmland dynamics in the context of a changing landscape, we mapped the land use/cover pattern in ArcGIS 10.2, and illustrated the structural changes over time. Further, we quantified the gain intensity and loss intensity of each land use/cover type in each study period. The gain intensity is defined as the ratio of gained area between time $t$ and $t+1$ to the total area at time $t+1$; while the loss intensity is defined as the ratio of lost area between time $t$ and $t+1$ to the total area at time $t$. Also, we visualized the conversions between different land use/cover types in each study period. In so doing, farmland changes can be interpreted in comparison to changes in other land use/cover types and in relation to the conversions between farmland and the other six land use/cover types.

**5.2.3. Socioeconomic and Agrifood Dynamics Analyses**

To link the farmland loss and landscape changes to human-environment interactions, data on socioeconomic and agrifood dynamics in Tongling core and periphery were collected for 2000-2015 from various sources. To reveal demographic trends, the mean and CV of population density were calculated after LandScan 2000-2015 (https://landscan.ornl.gov/), with a resolution of about 1km (Bright et al. 2016). Besides, average household size was also analyzed based on Anhui Statistical Yearbooks 2001-2016 (http://tjj.ah.gov.cn/), for its relevance to housing demand. To reveal economic development trends, we calculated GDP per capita, gross industrial output per capita, and total retail sales of consumer goods per capita based also on Anhui Statistical Yearbooks 2001-2016. For comparability, all the economic data were converted to U.S. dollar in 2015 based on official exchange rate between Chinese yuan and U.S. dollar at each year.
(https://www.usinflationcalculator.com/). GDP per capita is a core indicator for
diagnosing economic development stages according to World Bank’s industrialization
stages theory (Chenery et al. 1975), with often associated changes in the proportion of
agricultural employments and GDP structure of the primary, secondary, and tertiary
industries (Table 5.6). The Chenery diagnosis criteria are well-established based on
empirical findings during 1950-1970, but can be somewhat outdated especially in terms
of ratio of agricultural employment and GDP structure, because of new economic
activities like online business.

Table 5.6
Development stages by GDP per capita and associated changes, based on Chenery et al.
(1975).

<table>
<thead>
<tr>
<th>Industrialization stage</th>
<th>Pre-Industrialization</th>
<th>Mid-Industrialization</th>
<th>Late-Industrialization</th>
<th>Post-Industrialization</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP per capita (2015 $)</td>
<td>&lt; 1710</td>
<td>1710-3421</td>
<td>3421-6842</td>
<td>6842-12828</td>
</tr>
<tr>
<td>Agricultural employment ratio</td>
<td>&gt; 60%</td>
<td>45%-60%</td>
<td>30%-45%</td>
<td>10%-30%</td>
</tr>
<tr>
<td>GDP structure (A: I: S)*</td>
<td>A &gt; 1</td>
<td>A &gt; 20%, A &lt; I</td>
<td>A &lt; 20%, I &gt; S</td>
<td>A &lt; 10%, I &gt; S</td>
</tr>
</tbody>
</table>

*Note: A, I, and S, stand for the primary, secondary, and tertiary industries, respectively.

For agrifood dynamics, we examined the temporal trends of six indicators, including
total sown area of grain, total grain output, mean grain yield, proportion of people
entitled to farmland, intensity of agricultural machinery power usage, and intensity of
chemical fertilizer usage. The data are mainly from Anhui Statistical Yearbooks 2001-
(http://www.tl.gov.cn/), supplemented by indicator-specific searches in China Statistical
Yearbooks Database (http://tongji.cnki.net/). These data can help understand the
potential impacts of farmland loss on grain self-sufficiency – a national food security target of China – and the relation between farmland loss and agricultural intensification.

Finally, to detect potential regime shift in the socioeconomic and agrifood dynamics, we conducted changepoint detection to the twelve time-series, using the R-package ‘trends’ (Pohlert 2015). Specifically, the Mann–Kendall test was first conducted to detect if any statistically significant \( p < 0.05 \) monotonic trend exists, followed by the Pettitt’s test to determine if any statistically significant \( p < 0.05 \) changepoint occurs. The techniques have been widely used in various contexts (Li et al. 2017, Fang et al. 2018).

5.3 Results

5.3.1. Farmland Loss in Changing Core-Periphery Landscape

From 2000 to 2015, considerable farmland was lost to primarily developed lands, occurring in mostly Tongling core and the adjacent downtown of Tongling periphery (Fig. 5.2Aa). Over time, the farmland loss to developed lands had expanded from core to periphery, initially dominated by urban encroachment yet with increasingly balancing uptakes from urban built-ups, rural settlement, and other construction needs of industry, mining, and transportation (Figs. 5.2Ab-Ad). To be precise, farmland loss in the study area during 2000-2015 added up to a total of 98.64 km\(^2\) (i.e., 9.61% of the core-periphery system and 18.71% of the total farmland in 2000), which increased over time (Fig. 5.2Ba). The increasing trend of farmland loss area also applied to Tongling core and the periphery (Figs. 5.2Bb-Bc). Changes in farmland loss structure were also consistent at large among the core, periphery, and the whole, with the contribution of developed lands the lowest in 2000-2005, the highest in 2005-2010, and moderate in 2010-2015 ranging
wildly from 40% to almost 100% (Figs. 5.2Ba-Bc). Interestingly, the ratio of farmland loss to urban expansion was on a decreasing trend in Tongling core, yet bumped during 2005-2010 in Tongling periphery (Figs. 5.2Bb-Bc). The ratio varied wildly from 14.72%-74.36%, with its trend of the core-periphery system dominated by that of the periphery (Figs. 5.2Ba-Bc). In general, the amount and structure of farmland loss changed similarly over time for the core, periphery, and the whole system, with only different trends of urban encroachment of farmland.

Regarding the trends of farmland pattern changes, interestingly, the core, periphery, and the whole system all showed an abnormality in 2005-2010 (Fig. 5.2C). Aside from this abnormality, the three shared consistent trends of generally decreasing patch size, increasing shape complexity, and also increasing patch isolation (Figs. 5.2Ca, Cc, Ce, and Cf). Yet, the core and the periphery differed in terms of their spatial variations in patch size and shape complexity, with the core becoming more homogeneous and the periphery more heterogeneous (Figs. 5.2Cb and Cd).
Figure 5.5 Farmland transition in the core-periphery system. (A) Farmland loss areas and structures in the whole Tongling, Tongling core, and Tongling periphery. (B) Spatial distribution of different farmland loss types during 2000-2005, 2005-2010, 2010-2015, and 2000-2015. (C) Pattern changes of farmland – area, shape, and adjacency – from 2000 to 2015 for the whole Tongling, Tongling core, and Tongling periphery. CV refers to coefficient of variation.

For dynamics of the whole landscape, urban development occurred in mainly the edge-expanding mode, with drastic expansion in especially 2005-2010 (Fig. 5.3A). Besides, industrial, mining, and transportation land had expanded notably in 2010-2015 (Fig. 5.3A). The expansion of these developed lands was at the cost of mainly farmland (Fig. 5.3B). Nonetheless, the whole landscape was dominated by farmland and
densely/moderately vegetated land, with developed lands occupying relatively small portions in especially the periphery (Fig. 5.3B). Thus, the landscape though changed violently in the core (Fig. 5.3Bb), was quite stable in the periphery – 80% of the study area (Fig. 5.3Ba and Bc).

The spatiotemporal dynamics of each land use/cover type were contrasting in terms of both gain and loss (Fig. 5.4). Land gains were dominated by the expansion of developed lands throughout the three study periods. In particular, for both the core and the periphery, urban built-up land had the strongest gain intensity in 2005-2010 while rural settlement experienced strong gain intensity in both 2005-2010 and 2010-2015.

Figure 5.6 (A) Landscape patterns and (B) land use/cover structures of the core-periphery system in 2000, 2005, 2010, and 2015, with the temporal changes featured by developed land expansion and farmland loss.
Contrastingly, land losses were the most intensive in 2010-2015 for almost all land/use cover types for both the core and the periphery, and in particular, the losses of natural lands and farmland had become increasingly intense over time. An exception was the loss of densely/moderately vegetated land in Tongling core, which was most intensive in 2005-2010.

![Image of land use/cover type conversions](image)

**Figure 5.7** Each land use/cover type’s (A) gain intensity and (B) loss intensity during 2000-2005, 2005-2010, and 2010-2015, for the whole Tongling, Tongling Core, and Tongling Periphery. See text for explanations on calculating gain intensity and loss intensity. Land gains were dominated by developed lands whereas land losses of natural lands and farmland became intensified through time.

There were three notable patterns of the inter-conversions between different land use/cover types (Fig. 5.5). Firstly, consistent with Fig. 5.4, the land use/cover conversions were dominated by losses of farmland and densely/vegetated land and the gains of developed lands, especially in 2005-2010. Secondly, farmland loss area
accounted for the most land use conversions (44%-77%), except for Tongling core in 2000-2005 (8%); and over time, the ratio decreased generally. Thirdly, land use conversion structures of the core and the periphery differed except in 2005-2010; the core was featured by the conversion from urban built-up land to densely/moderately vegetated land as well as inter-conversions between developed lands (Fig. 5.5B), while the periphery had unique conversions between densely/moderately vegetated land and farmland as well as the conversion from rural settlement to farmland (Fig. 5.5C).

![Figure 5.8](image-url)  
**Figure 5.8** Land use/cover conversion flows during 2000-2005, 2005-2010, and 2010-2015, for (A) Tongling, (B) Tongling Core, and (C) Tongling Periphery. Flow size is proportional to the total land use conversions in an area during a period, non-comparable between each subfigure. Flow direction goes from the right side of the source land use/cover type to the left side of the sink land use/cover type. For visibility, flows below 5% are not shown.

### 5.3.2. Socioeconomic and Agrifood Dynamics

Probable regime shifts were detected at mostly 2007 in the socioeconomic dynamics of both the core and the periphery, with two exceptions at 2006 for the mean and CV of
population density in Tongling periphery (Fig. 5.6). For demographic dynamics, the population density decreased in the periphery, while increased in Tongling core (Fig. 5.6 Aa); population of Tongling periphery had become spatially more concentrated over time, while that of the core had first increased and then decreased (Fig. 5.6Ab); and consistent between the core and the periphery, the average household size continued to decline from over 3.4 to below 3.0, with that of the periphery stabilized somehow since 2010 after reaching 2.8 (Fig. 5.6Ac). For economic dynamics, the core and periphery both presented increasing trends of economic development in general (Fig. 5.6Ba) and the developments of the secondary and tertiary industries in particular (Figs. 5.6Bb and Bc), though all with enlarged core-periphery gaps. Notably, there was a slowdown at 2009 and a quick catch-up thereafter in terms of Tongling core’s GDP per capita and gross industrial output per capita (Figs. 5.6Ba and Bb). By the Chenery industrialization and development stages diagnosis criterion of GDP per capita (Table 5.6), Tongling core entered mid-industrialization in 2003, late-industrialization in 2006, and post-industrialization in 2010, while Tongling periphery entered early-industrialization in 2007 and mid-industrialization in 2014 (Fig. 5.6Ba).
Figure 5.9 Socioeconomic dynamics of the core-periphery system during 2000-2015, with statistically significant ($p < 0.05$) probable changepoints marked by dashed lines. CV refers to coefficient of variation.

For the agrifood dynamics that were more closely related to farmland changes, probable regime shifts were also detected at different years between 2005-2010, depending on the indicator and focal area (Fig. 5.7). For particularly the dynamics of grain production (Fig. 5.7A), in Tongling periphery, the sown area of grain decreased until 2007, resulting in the decreasing total grain output despite the increased grain yield; while in Tongling core, the sown area of grain increased remarkably especially before 2009, resulting in the increasing total grain output despite the decreased grain yield.

Interestingly, trends of total grain sown area, total grain output, and mean grain yield all showed convergence between the core and the periphery, especially since around 2008. The dynamics of agricultural intensification was quite stable for both the core and the periphery, with the periphery more intensified than the core (Fig. 5.7B). Specifically, the proportion of people entitled to farmland was on a very slow decreasing trend for the core and the periphery; while the intensities of agricultural machinery power usage and
chemical fertilizers usage showed increasing trends until around 2006. The correlated data together showed that 2005-2010 was a critical transitional period for agrifood dynamics of the core-periphery system.

![Figure 5.10](image)

**Figure 5.10** Agrifood dynamics of the core-periphery system during 2000-2015, with statistically significant ($p < 0.05$) probable changepoints marked by dashed lines.

### 5.4 Discussion

#### 5.4.1. Temporal Trends of Farmland Loss During Drastic Urbanization

Farmland loss is widely reported in drastically urbanizing areas, with arguably urban expansion to blame. There has been a decades-long policy debate on whether and how to prevent farmland from urban encroachment (Alterman 1997, Edgens and Staley 1999, Gottlieb 2015), largely because existing studies tend to focus narrowly on urban sprawl and the resulting farmland loss. For a more comprehensive understanding of the UAFL issue, we argued for adopting a landscape sustainability perspective to examine the spatiotemporal trends of farmland loss as well as the urbanizing landscape where farmland is embedded. To this end, we conducted a case study of a core-periphery system in China (Fig. 5.1) during 2000-2015, when the population urbanization level of
the study area increased from 57.43% to 79.41%. We found a set of temporal trends shared by the core and the periphery.

Firstly, changes of the whole landscape were featured by persistent aggressive land gains of developed lands (including urban built-up land, rural settlement, and industrial, mining and transportation land) and increasing land losses of not just farmland but also densely/moderately vegetated land (Fig. 5.4). This accords well with the empirical theory of land use transition that along with regional development, human-dominated lands would expand, natural lands would shrink, while farmland as the semi-natural land would first increase and then decrease (DeFries et al. 2004, Mustard et al. 2004). Also, it is no surprise from the “develop versus sustain” landscape sustainability perspective, as the human subsystem expands at the cost of the shrinkage of the environment subsystem. This perspective also explains the contrast that the core experienced drastic landscape transformations while the periphery was relatively stable (Fig. 5.3). The direct implication of this trend is that attention needs to be paid to the loss of semi-/natural lands in rapidly developing areas, while on the other hand, this trend suggests that farmland loss can be a trivial concern for urbanization in areas where farmland is not the dominant type of semi-/natural lands. For example, in the case of urbanization in the desert city of Phoenix, Arizona, USA during 1985-2005, new urban land was converted more from desert and dense vegetation than from farmland (Buyantuyev et al. 2010).

Secondly, there was considerable and increasing amount of farmland loss over the three study periods (Fig. 5.2B) – unsurprising given the study area’s rapidly growing economy (Fig. 5.6B) – but the ratio of farmland loss area to total land conversion
decreased in general (Fig. 5.5). This suggests that economic development would lead to increasingly drastic landscape modifications, among which the intensified farmland loss should become comparatively less central. Because along with development there are new land use/cover changes becoming intensified, such as the conversion from urban built-up land to densely/moderately vegetated land and inter-conversions between developed lands in the core (Fig. 5.5B) and the conversions between densely/moderately vegetated land and farmland and the conversion from rural settlement to farmland in the periphery (Fig. 5.5C). The human-environment interactions underlying these land use/cover changes have sustainability implications different from those of farmland loss. For example, the conversion from urban built-up land to vegetation can affect environmental injustice (Fernández and Wu 2018), and the conversion from rural settlement to farmland in China very likely involves a nationwide policy known as “Farmland Dynamic Balance” for actively balancing lost farmland, which has a big stake for farmers and the local government (Zhang et al. 2014, Shen et al. 2017).

Thirdly, since 2005, farmland had become smaller in patch size, less regular in patch shape, and more isolated between patches, which were more so in the core than in the periphery (Fig. 5.2C). These trends suggest agricultural deintensification, as echoed by the decreasing or stabilizing machinery power use intensity and chemical fertilizers use intensity (Fig. 5.7B). Jiang et al. (2013) also reported the association of urban encroachment of farmland with decreasing agricultural land use intensity in China based on panel econometric modeling. Their findings support the market-based hypothesis that highlights the influences of higher market demands and better off-farm employment
opportunities due to urbanization, with market demands less influential in open economies (see the article for an overview of the competing hypotheses). On the other hand, studies have shown that agricultural intensification increases the economic viability of farming and further causes agricultural expansion (Rudel et al. 2009, Lin and Huang 2019). Therefore, the cooccurrence of farmland shrinkage and agricultural deintensification in our study area most likely indicates the decreasing economic viability of farming during drastic urbanization, with agricultural labors having lower individual opportunity costs (e.g., the aged who often cannot find urban off-farm employments). In this sense, our results support the argument that farmland loss is more of an economic issue than a resource issue (Edgens and Staley 1999), which points to the need to increase farming profitability when food security is the focal point of sustainability concern.

5.4.2. Temporal Abnormalities of Farmland Loss and Why

In the context of the temporal trends identified above, we unexpectedly found three temporal abnormalities in the trends of farmland loss, land conversions, as well as socioeconomic and agrifood dynamics. Understanding what caused these temporal abnormalities is critical for projecting future trends of UAFL and thus sustainability policymaking. Below we evaluate what internal structural change or abrupt external disturbance was responsible, if any.

First, the structure of land conversions differed between the core and the periphery except in 2005-2010, when both were dominated by the conversions from semi-/natural lands to developed lands (Fig. 5.5b). Our initial hypothesis is potential socioeconomic regime shifts in Tongling core and Tongling periphery, as corroborated by the detected
changepoints in 2005-2010 (mostly at 2007) (Fig. 5.6). However, the Chenery standard of GDP per capita (Table 5.6) suggests desynchronized changes: The core transitioned from late-industrialization in 2006 to post-industrialization in 2010, while the periphery transitioned in 2007 from pre-industrialization to early-industrialization (Fig. 5.6Ba). Alternatively, the core and the periphery’s similar land use conversion structures can be attributed to some external shock, e.g., the financial crisis of 2007-08 and consequently, the Chinese government’s Four Trillion Investment Plan launched in November 2008 to stabilize economy (Naughton 2009). This massive investment plan led to a burst nationwide in affordable housing projects, rural infrastructure construction, and the construction of major infrastructure such as railways, highways and airports. The massive investment burst hypothesis also explains why in 2005-2010 almost all the lost farmland was converted for development, and why the proportion to urban expansion decreased in the core yet increased sharply in the periphery (Fig. 5.2B) – because Tongling core was already highly urbanized while the periphery still had a big urbanization potential. Thus, we propose to understand the detected changepoint around 2007 (Fig. 5.6B) as a shift toward a post-crisis economic regime.

Second, the ratio of farmland loss to the total land use conversion in Tongling core was an abnormally low 8% in 2000-2005, as opposed to the high and decreasing ratios in 2005-2010 and 2010-2015 – 54% and 44%, respectively (Fig. 5.5B). Yet, in 2000-2005, there was 48% of the total land conversion going to urban development, indicating this was not a demand side issue as in the above case but a sudden drop of farmland scarcity. The drop could have occurred any time during 2000-2010, which cannot be identified
from the land use/cover data we had for every five years. Theoretically, the farmland scarcity can be biophysical scarcity as in the desert city of Phoenix, Arizona, USA (Buyantuyev et al. 2010), or institutional scarcity which is common in places like China where exclusive zoning and land use quotas system are implemented (Chien 2015, Wang et al. 2020). Here for Tongling core, it was both. In fact, Tongling had two major administrative boundary adjustments that expanded Tongling core. In November 2004, Tongling core annexed Datong Town (153.98 km²) from Tongling periphery, through which it expanded by 256.12% from 60.12 km² to the current 214.10 km²; in late 2001, Tongling core annexed Xihu Town (ca. 30 km²) from Tongling periphery, through which it expanded by 99.60% from 30.12 km² in 2001 to 60.12 km² in 2004. The large quantity of farmland gained in the annexation processes increased the potential supply of farmland conversion for developed land expansion, leading to farmland loss becoming the main land use conversion source in 2005-2010 and 2010-2015. This farmland quotas reallocation hypothesis also explains the increasing grain sown area in Tongling core and the decreasing grain sown area in Tongling periphery especially in 2000-2005 (Fig. 5.7Aa).

Third, opposite from the trends of farmland pattern changes from 2005 to 2015 that indicate agricultural deintensification, the trends from 2000 to 2005 indicate agricultural intensification – more so in the periphery than in the core (Fig. 5.2C). This critical transition from agricultural intensification to deintensification could have occurred any time during 2000-2010 and again cannot be identified from the land use/cover data we had for every five years. Yet, based on the detected changepoints of agrifood dynamics
in 2005/2006/2007/2009 (Fig. 5.7), it was more likely to have occurred during 2005-2010. In the above section, we have argued that the agricultural deintensification in 2005-2010 and 2010-2015 were due to the decreasing economic viability of farming as compared to non-agricultural industries. The same economic rationale can explain the agricultural intensification of the core and the periphery in 2000-2005. Recall that by the Chenery standard (Table 5.6), Tongling core started mid-industrialization in 2000 and in 2006 reached late-industrialization, during which its dominant industry shifted from the primary to the secondary; while Tongling periphery stayed in per-industrialization before 2007 with agriculture as its dominant industry. This implies that farmers in Tongling core had higher opportunity costs than their periphery counterparts, which explains the core’s lower agricultural intensity (Fig. 5.7B). More importantly, that both the core and the periphery showed agricultural intensification trend in 2000-2005 could result from either decreasing economic viability of the non-agricultural industries – which was not the case (Fig. 5.6B) – or increasing economic viability of farming. Indeed, FAO food price index shows that food prices had been increasing since 2000 up to 2008 (http://www.fao.org/worldfoodsituation/foodpricesindex). Another hypothesis that we tend to reject is the abolition of agricultural tax across China during 2003-2005, because studies have found it to have statistically insignificant impacts on agricultural production (Heerink et al. 2006, Wang and Shen 2014).

5.4.3. Policy Implications and next Research Steps

By taking the landscape sustainability perspective, our case study has come to three general lessons about the UAFL phenomena for rethinking farmland preservation
policymaking. Firstly, as essentially driven by the expansion of the human subsystem, farmland loss will continue to occur and increase over the course of regional socioeconomic development, even after reaching the terminal stage of urbanization (United Nations 1974, Mulligan 2013). Secondly, whether farmland loss deserves policy efforts is dependent on the “develop versus sustain” sustainability tradeoff within the constraint of farmland natural land endowments. Thirdly, farmland loss is more an economic issue than a resource issue, and can be regulated through policy interventions to farmland demand and supply. In rapidly developing, densely populated areas like China and India, farmland loss deserves legitimate concern. Yet, our results have shown that urban encroachment of farmland accounted for 14.72%-74.36% of total farmland loss, with the ratio presenting remarkable spatiotemporal variations (Fig. 5.2B). This challenges the popular framing that urban expansion onto farmland undermines food security, which limits policy attention to arguably containing urban development (Fischel 1982, Edgens and Staley 1999, Gottlieb 2015).

Instead, we argue to shift the policy efforts to addressing the injustice in farmland preservation per se, by explicitly recognizing farmland preservation as a collective action problem. We disagree with the belief that “market-based approaches to farmland protection will ensure an adequate food supply” (Edgens and Staley 1999). Market needs time to respond to food shortage due to abrupt events (e.g., climate extremes and trade wars), and more importantly, “the invisible hand” will lead to free-riding in collective action arenas. China has long been taking proactive farmland preservation policies that are featured by top-down land conversion quotas (Zhang et al. 2014, Chien 2015, Shen et
al. 2017). Yet, our results have shown the considerable and increasing farmland loss in Tongling core and Tongling periphery, with both experiencing agricultural deintensification since 2005 (Figs. 5.2 and 5.7). The municipal government of Tongling City even reallocated land resource from the periphery to the core by administrative boundary adjustments so to provide the core with enough farmland conversion quotas for development (Fig. 5.5B). In fact, due to the relatively low economic viability of farming, China’s local governments in the rapidly developing areas often overshoot top-down land conversion quotas (Wang et al. 2020). In this regard, there emerged a bottom-up market-based initiative by some regional governments in China, i.e., the land conversion quotas trading scheme similar to trading of development rights, which has been found able to improve the economic performances of both the buyers and sellers (Zhang et al. 2014). This policy experiment to integrate top-down and bottom-up approaches for addressing the collective action of farmland preservation seems promising for the study area, other places of China, and likely also other countries.

Our study is atypical of the existing landscape sustainability literature (Opdam et al. 2006, Liu et al. 2020), more attempting to report and understand the landscape features of a widespread landscape-relevant sustainability challenge. We found that some of the landscape features have a good potential to infer underlying human-environment processes, e.g., the use of landscape metrics of farmland pattern to depict agricultural intensity (Figs. 5.2C and 5.7B). We also found that the amount and structure of farmland loss are not related to the economic development stage (Figs. 5.2B and 5.6Ba). In medical sciences, reporting the clinical features of a new disease is important for
understanding its pathology and making prognosis (Huang et al. 2020); in development economics, the meta-analysis of socioeconomic features of development also provides foundational basis for economic policymaking (Chenery et al. 1975). However, it is no easy task, if not impossible, to single out meaningful landscape indicators for the problem-driven, diagnostic landscape sustainability research (Zhou et al. 2019). Further research along this line will depend heavily on large number of case studies with comprehensive data on landscape change and social, economic and environmental dynamics, after which indicators of landscape patterns can be linked to human-environment outcomes by methods like meta-analysis, pattern-oriented modeling, and machine-learning based approaches.

5.5 Conclusion

This paper attempts to explore the problem-driven, diagnostic landscape sustainability research (Chapter 3), through a comparative study to understand the changing landscape features of a widespread and controversial challenge – farmland loss during drastic urbanization. The case study area has a special core-periphery structure, which allowed us to identify a few temporal trends and abnormalities of farmland loss, landscape change, and related socioeconomic and agrifood dynamics. For one, considerable and increasing amount of farmland were lost in both the core and the periphery during 2000-2015 yet with remarkably variant proportion to urban expansion (i.e., 14.72%-74.36%). It explains the controversial claims in existing studies on holding urban expansion to blame for farmland loss. For another, farmland loss was generally associated with agricultural deintensification, which would pose double negative impacts
on regional food supply. Moreover, we found abnormalities such as agricultural intensification and very mild farmland loss in certain period, which could be explained by the general economic rationale of farmland demand-supply changes.

Our findings suggest that farmland loss deserves policy attention in rapidly developing, densely populated areas, even at the terminal stage of urbanization. For policy interventions, we argue that the narrow focus on urban development versus farmland preservation is misleading, and that instead, efforts are needed to attend the collective action dilemma of implementing farmland preservation for common food security. In this regard, it seems promising by integrating a top-down land conversion quotas scheme with a bottom-up land quotas trading scheme, based on policy experiments in China. The study of farmland loss over the course of regional socioeconomic development is of central relevance to the practice and science of landscape sustainability, by shedding light on the “develop versus sustain” sustainability tradeoff that applies to other issues like agricultural expansion at the cost of deforestation. Our analysis shows that some landscape indicators such as patch size and fractal dimension are useful for inferring from landscape features their underlying human-environment processes. We highlight that the promise of this problem-driven, diagnostic approach to landscape sustainability will depend heavily on generating high temporal resolution landscape data and collecting comprehensive socioenvironmental data.
6.1 Summary of Major Findings

Recall that the twofold aim of this dissertation is to communicate what landscape sustainability research (under the convenient label of LSS) is all about in terms of science and practice. I took a sustainability science perspective and a historical perspective to articulate what the scientific foundations of LSS are – deeply rooted in landscape ecology, partially influenced by land system science, and increasingly embracing sustainability science. To demonstrate the problem-driven, diagnostic approach to landscape sustainability research, I focused on specifically the urbanization-associated farmland loss (UAFL) issue, which remained a decades-long, worldwide debate regarding whether and how to protect farmland from urban development for the sake of food security. I address the theoretical part with Chapters 2 and 3, and the empirical part with Chapters 4 and 5. The major findings of each research chapter are as follows:

Chapter 2: Distinguishing Sustainability Science from Conventional Sustainable Development Research

We found: (1) Sustainability science (SS) reformulates sustainable development (SD) as part of the social-environmental system, whereas the conventional SD research focuses on various sectoral issues. (2) SS is increasingly moving from integrative science assessment to transdisciplinary science-action, while SD research at large has moved from a global change to a business-industrial emphasis. (3) SD has been losing public interests since 2004 until 2015 when Sustainable Development Goals were launched,
while SS has received rapidly growing interests from 2006 onward. Our findings reject the null hypothesis, and demonstrate that sustainability science is a new and expanding science that bridges the much larger volumes of the conventional disciplinary sustainable development studies. We argue that core to sustainability science are two perspectives: the complex human-environment systems perspective (complexity) and increasingly, the transdisciplinary perspective (value-ladenness/normativeness).

Chapter 3: Research Progress and Knowledge Gaps of Landscape Sustainability Science: A Multi-Method Bibliometric Review

We found: (1) Sustainability studies of landscapes have entered a rapid growth phase since 2004-2006, as determined statistically by the annual publications and citations; (2) There have been many more studies focusing on the ecological and practical dimensions than sociocultural and theoretical dimensions; and (3) Influenced by advances in sustainability research in a broader science context, studies of SL and LS have become increasingly holistic, transdisciplinary, and normative. Our findings suggest a transdisciplinary science on sustainability studies of landscapes in its formation (i.e., LSS) in the past fifteen years. The results also help clarify some of the key concepts of LSS, and highlight the need of further instilling sustainability science into LSS, e.g., the human-environment systems and transdisciplinary perspectives. We identify in the existing LSS literature a major knowledge gap on understanding the un/sustainability of human-environment systems through a landscape lens, and advocate for the problem-driven, diagnostic approach to advancing landscape sustainability.
Chapter 4: Urbanization-Associated Farmland Loss in Core and Periphery Areas: A Macro-Micro Comparative Study in China

We found: (1) The percentage of farmland loss to urban encroachment remained below one third in the southeast urban China during 2000-2015, and increased in the northwest rural China from below one tenth before 2010 to about one fourth thereafter. (2) Urban encroachment of farmland was complained by 14.89% surveyed peri-urban farmers and 1.92% rural farmers for reducing grain-production; 29.79% peri-urban and 36.54% rural households converted farmland for residential use during 2000-2015; while farmland conversion for non-grain production uses accounted for 93.33% and 55.22% of the total farmland losses of the peri-urban and rural households, respectively. (3) The top considered factors in grain-production decision-making of the peri-urban and rural households were irrigation (55.32% versus 40.38%), grain-production cost (46.81% versus 53.85%), and grain-selling price (36.17% versus 36.54%). (4) The peri-urban households had an average rice deficit of -364kg while the rural households had a surplus of 312kg. (5) In both villages, two thirds of the surveyed farmers preferred rural living and around a half were willing to farm; while the ratios for their younger generation were one fifth and one tenth, respectively. Our findings have rejected all the null hypotheses that urban expansion is responsible for farmland loss, that farmland loss is responsible for decreasing grain production; and that decreasing grain production instead of increasing grain demand is responsible for grain self-insufficiency. Thus, we argue that the problem framed as that urban expansion onto farmland threatens food security is “fake,” and that
UAFL can cause sustainability problems other than food security which remain to be identified.

Chapter 5: Understanding Temporal Features of Farmland Loss in Drastically Urbanizing Core-Periphery System: A Landscape Sustainability Perspective

We found: (1) Considerable, increasing amount of farmland loss occurred in the core and periphery of Tongling during 2000-2015, when its population urbanization level increased from 57.43% to 79.41%. (2) Urban encroachment of farmland accounted for 14.72%-74.36% of total farmland loss, with the ratio changing remarkably through time. (3) Farmland became smaller in patch size, less regular in patch shape, and more isolated between patches, with the core becoming spatially more homogeneous while the periphery more heterogeneous. (4) For changes of the whole landscape, land gains were persistently dominated by expansion of developed lands (including urban built-up land, rural settlement, and industrial, mining and transportation land), while all land use/cover types experienced the most intensive loss in 2010-2015 and in particular, the loss intensity of natural lands and farmland increased over time. (5) Farmland loss area accounted for 8%-77% of total land use conversion, with the ratio generally decreasing during 2000-2015. (6) Land use conversion structures of the core and the periphery differed except in 2005-2010, when probable regime shifts were detected in their socioeconomic and agrifood dynamics. Our findings suggest that farmland loss and urban expansion are associated outcomes of development processes, or say, human subsystem expansion at the cost of the environment subsystem. Farmland loss can continue even at the terminal stage of urbanization, as long as other development
processes continue such as the expansion of rural settlement or infrastructure; and farmland loss can be trivial even during drastic development periods in cases where other land use/cover resources such as forest and rural settlement can meet the land demands of development. Our findings imply that UAFL is more of an economic issue than a resource issue, and suggest that—as the comparatively low economic viability of farming disincentivizes all lower-level stakeholders to sacrifice their development needs for preserving farmland—the real problem regarding the UAFL issue is social injustice in the collective action of farmland preservation to ensure collective food security. In order to more effectively mobilize stakeholders to meet the target of farmland preservation in some regions (for actual/potential food insecurity or other considerations), we advocate this social injustice problem framing of UAFL and discuss China’s innovational top-down and bottom-up land management institutions as a potential policy prescription.

6.2 Significance of Research

This dissertation contributes to the field of LSS in the three following ways:

- Articulating that advancing sustainability though the landscape lens on human-environment dynamics is timely and much needed because (1) landscape science has a pretty long history of studying sustainability dating back to the late 1980s; (2) it has gained notable momentum since 2004-2006, with a converging and growing research community since around 2013; and (3) as an emerging field, it still has major gaps in its scientific foundations to be filled and needs many more empirical studies to be conducted.
• Calling attention to the core of sustainability science – the complex human-environment systems perspective and the value-laden transdisciplinary perspective – that some LSS pioneers are increasingly embracing, and to the problem-driven, diagnostic approach to enhancing landscape sustainability that remains underused in the LSS community. If the LSS community can move beyond the more ecology and practice-focused landscape ecology tradition and further embrace sustainability science, LSS will be able to make larger contributions to the science and practice of sustainability.

• Showing that the popular problem framing that urban expansion onto farmland threatens food sufficiency is inappropriate. Farmland loss is more an issue of farming lacking economic viability than biophysical farmland scarcity. I advocate to direct policy attention to the social injustice problem that is embedded in the collective action dilemma of preserving farmland for regional and global food sufficiency—whose development right to sacrifice. In this regard, policymakers can be referred to an innovational policy prescription successfully implemented in China, which integrates a top-down land use conversion quotas scheme with a bottom-up quotas trading scheme.

6.3 Limitations and Future Directions

There are two main methodological limitations in Chapters 2 and 3. Depicting the research landscapes of sustainability science and sustainable development studies based on bibliographic data is only one approach, which underrepresents subfields that cannot be identified by the used keywords (e.g., land system science) and overrepresents
subfields that usually get higher average of citations (e.g., energy studies, sustainability education). An alternative approach is to do a large-sample survey of the sustainability research community asking for their perceptions on the differences between sustainability science and conventional sustainable development research, similar to Miller (2013). A second alternative approach is to analyze a diversity of representative descriptions or documents on the two as in Fang et al. (2018), e.g., William Clark has repeatedly defined sustainability science as the use-inspired, basic research strand of the larger sustainable development research enterprise (Clark 2007, Clark and Harley 2019). Due to the similar limitations embedded in the bibliometric approach, the research landscapes of LSS captured in Chapter 3 does not well reflect the intellectual footprint of the land system science community. It will be helpful to conduct a separate bibliometric analysis of land system science by focusing on their explicit contributions to sustainability.

Chapters 4 and 5 are only case studies of the UAFL issue, yet unable to provide comprehensive documentation of how UAFL varies in different human-environment contexts. In this regard, it is necessary and will be fruitful to conduct large-N case studies and subsequent pattern recognition of UAFL, as in the emerging syndrome-based or archetypal studies (Schellnhuber et al. 2002, Lüdeke et al. 2004, Srinivasan et al. 2012, Stellmes et al. 2013, Dee et al. 2017, Levers et al. 2018, Oberlack et al. 2019). In so doing, a comprehensive archive of the UAFL syndrome can be built for general diagnostic purposes as in Huang et al. (2020), and for syndrome prevention by assessing each place’s vulnerability/disposition as conducted by Schellnhuber et al. (2002).
The empirical findings provide diagnostic knowledge about the UAFL issue with tentative policy suggestions for action. To further link the knowledge with action, prognostic and transformational studies need to be conducted in the future. In this regard, pattern-oriented modeling (Grimm et al. 1996, Janssen et al. 2009) seems promising to move from diagnosis to prognosis. The core task is to build mechanistically realistic agent-based models (ABMs) that must be able to replicate the landscape symptoms and associated social-environmental complications of UAFL. Non-falsified ABMs can then be used to prognose the likely social-environmental synergies and trade-offs, by encoding typical policy treatments as new feedbacks of the model. Based on participatory sustainability assessment of the simulated human-environment synergies and trade-offs, the type, magnitude, and timing of policy prescriptions can be implemented to transform a specific UAFL-struck place toward desired sustainable future.

Lastly, to further apply the problem-driven, diagnostic approach for advancing landscape sustainability, a priority is to survey what long-term trends of land use and landscape change (Sleeter et al. 2013, Bürgi et al. 2017a, Song et al. 2018) are raising sustainability concerns (Foley et al. 2005, Turner II et al. 2007, Helming et al. 2008). On one hand, long-term place-based studies of land use and landscape change and synthesis of the case studies are needed; on the other hand, a sustainability perspective on the case studies should be promoted, for which a major challenge remains that conventional land use/cover analysis needs to be extended to link land use functions to human needs and wellbeing (Verburg et al. 2009, Wu 2013b).
REFERENCES


Lambin, E. F., B. L. Turner II, H. J. Geist, S. B. Agbola, A. Angelsen, J. W. Bruce, O. T. Coomes, R. Dirzo, G. Fischer, and C. Folke. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change* **11**:261-269.


Liu, Z., C. He, Y. Yang, and Z. Fang. 2020. Planning sustainable urban landscape under the stress of climate change in the drylands of northern China: A scenario analysis based on LUSD-urban model. *Journal of Cleaner Production* **244:**118709.


Miyasaka, T., Q. B. Le, T. Okuro, X. Zhao, and K. Takeuchi. 2017. Agent-based modeling of complex social–ecological feedback loops to assess multi-

Mooney, H. 2016. Editorial overview: Sustainability Science: social–environmental systems (SES) research: how the field has developed and what we have learned for future efforts. *Current Opinion in Environmental Sustainability* 19:v-xii.


APPENDIX A

SUPPLEMENTARY INFORMATION, CHAPTER 2
Table S2.1
Overview of the sampled papers on *sustainable development* and *Sustainability Science*. Papers were selected on 03/14/2019 from Scopus (www.scopus.com) via searching in titles, abstracts, and keywords by <“sustainable development”> and <“Sustainability Science”>, respectively, limited to those published in the English language.

<table>
<thead>
<tr>
<th></th>
<th>Sustainable development</th>
<th>Sustainability Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of publications</td>
<td>1063</td>
<td>1063</td>
</tr>
<tr>
<td>Number of authors</td>
<td>4252</td>
<td>2648</td>
</tr>
<tr>
<td>Number of sources</td>
<td>417</td>
<td>414</td>
</tr>
<tr>
<td>Number of authors (journals, books, etc.)</td>
<td>4038</td>
<td>2392</td>
</tr>
<tr>
<td>Average citations per publication</td>
<td>342.2</td>
<td>33.44</td>
</tr>
<tr>
<td>Authors per publication</td>
<td>4</td>
<td>2.49</td>
</tr>
<tr>
<td>Authors of single-authored publication</td>
<td>214</td>
<td>256</td>
</tr>
<tr>
<td>Authors of multi-authored publication</td>
<td>4038</td>
<td>2392</td>
</tr>
<tr>
<td>Collaboration index*</td>
<td>4.9</td>
<td>3.14</td>
</tr>
</tbody>
</table>

*Note: The Collaboration Index is calculated as Total Authors of Multi-Authored Articles divided by Total Multi-Authored Articles*
**Table S2.2**  
Legend for the intellectual development paths of the sustainable development studies and Sustainability Science research (complement to Figure 2.3).

<table>
<thead>
<tr>
<th>Research domain</th>
<th>Top 25 most-cited publications</th>
<th>Title</th>
<th>Journal</th>
<th>Local citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainable development</td>
<td>Lélé 1991</td>
<td>Sustainable development: A critical review</td>
<td>World Development</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Kemp 1994</td>
<td>Technology and the transition to environmental sustainability. The problem of technological regime shifts</td>
<td>Futures</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Mebratu 1998</td>
<td>Sustainability and sustainable development: Historical and conceptual review</td>
<td>Environmental Impact Assessment Review</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Green et al. 1998</td>
<td>Green purchasing and supply policies: Do they improve companies' environmental performance?</td>
<td>Supply Chain Management</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Rennings 2000</td>
<td>Redefining innovation - Eco-innovation research and the contribution from ecological economics</td>
<td>Ecological Economics</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Holling 2001</td>
<td>Understanding the complexity of economic, ecological, and social systems</td>
<td>Ecosystems</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Rotmans 2001</td>
<td>More evolution than revolution: Transition management in public policy</td>
<td>Foresight</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Dyllick &amp; Hockerts 2002</td>
<td>Beyond the business case for corporate sustainability</td>
<td>Business Strategy and the Environment</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Balmford et al. 2002</td>
<td>Ecology: Economic reasons for conserving wild nature</td>
<td>Science</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Parris &amp; Kates 2003</td>
<td>Characterizing and measuring sustainable development</td>
<td>Annual Review of Environment and Resources</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Cash et al. 2003</td>
<td>Knowledge systems for sustainable development</td>
<td>Proceedings of the National Academy of Sciences</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Azapagic 2004</td>
<td>Developing a framework for sustainable development indicators for the mining and minerals industry</td>
<td>Journal of Cleaner Production</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Geels 2004</td>
<td>From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory</td>
<td>Research Policy</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Smith et al. 2005</td>
<td>The governance of sustainable socio-technical transitions</td>
<td>Research Policy</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Chisti 2007</td>
<td>Biodiesel from microalgae</td>
<td>Biotechnology Advances</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Zhu et al. 2007</td>
<td>Green supply chain management: pressures, practices and performance within the Chinese automobile industry</td>
<td>Journal of Cleaner Production</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Matos &amp; Hall 2007</td>
<td>Integrating sustainable development in the supply chain: The case of life cycle assessment in oil and gas and agricultural biotechnology</td>
<td>Journal of Operations Management</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Hekkert et al. 2007</td>
<td>Functions of innovation systems: A new approach for analysing technological change</td>
<td>Technological Forecasting and Social Change</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Seuring &amp; Müller 2008</td>
<td>From a literature review to a conceptual framework for sustainable supply chain management</td>
<td>Journal of Cleaner Production</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Schot &amp; Geels 2008</td>
<td>Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda, and policy</td>
<td>Technology Analysis and Strategic Management</td>
<td>8</td>
</tr>
<tr>
<td>Year</td>
<td>Authors</td>
<td>Title</td>
<td>Journal</td>
<td>Page</td>
</tr>
<tr>
<td>----------</td>
<td>-------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>----------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>2003</td>
<td>Mihelcic et al.</td>
<td><em>Sustainability Science</em> and engineering: The emergence of a new metadiscipline</td>
<td>Environmental Science and Technology</td>
<td>15</td>
</tr>
<tr>
<td>2003</td>
<td>Clark &amp; Dickson</td>
<td><em>Sustainability Science</em>: The emerging research program</td>
<td>Proceedings of the National Academy of Sciences</td>
<td>165</td>
</tr>
<tr>
<td>2004</td>
<td>Swart et al.</td>
<td>The problem of the future: <em>Sustainability Science</em> and scenario analysis</td>
<td>Global Environmental Change</td>
<td>32</td>
</tr>
<tr>
<td>2006</td>
<td>Wu</td>
<td><em>Landscape Ecology</em>, cross-disciplinarity, and <em>Sustainability Science</em></td>
<td><em>Landscape Ecology</em></td>
<td>19</td>
</tr>
<tr>
<td>2007</td>
<td>Ness et al.</td>
<td>Categorising tools for sustainability assessment</td>
<td>Ecological Economics</td>
<td>14</td>
</tr>
<tr>
<td>2007</td>
<td>Clark</td>
<td><em>Sustainability Science</em>: A room of its own</td>
<td>Proceedings of the National Academy of Sciences</td>
<td>103</td>
</tr>
<tr>
<td>2007</td>
<td>Ostrom</td>
<td>A diagnostic approach for going beyond panaceas</td>
<td>Proceedings of the National Academy of Sciences</td>
<td>34</td>
</tr>
<tr>
<td>2007</td>
<td>Kajikawa et al.</td>
<td>Creating an academic landscape of <em>Sustainability Science</em>: An analysis of the citation network</td>
<td><em>Sustainability Science</em></td>
<td>38</td>
</tr>
<tr>
<td>2008</td>
<td>Kajikawa</td>
<td>Research core and framework of <em>Sustainability Science</em></td>
<td><em>Sustainability Science</em></td>
<td>45</td>
</tr>
<tr>
<td>2011</td>
<td>Kates</td>
<td>What kind of a science is <em>Sustainability Science</em>?</td>
<td>Proceedings of the National Academy of Sciences</td>
<td>62</td>
</tr>
<tr>
<td>2011</td>
<td>Jerneck et al.</td>
<td>Structuring <em>Sustainability Science</em></td>
<td><em>Sustainability Science</em></td>
<td>61</td>
</tr>
<tr>
<td>2011</td>
<td>Wiek et al.</td>
<td>Key competencies in sustainability: A reference framework for academic program development</td>
<td><em>Sustainability Science</em></td>
<td>68</td>
</tr>
<tr>
<td>2012</td>
<td>Wiek et al.</td>
<td>From complex systems analysis to transformational change: A comparative appraisal of <em>Sustainability Science</em> projects</td>
<td><em>Sustainability Science</em></td>
<td>34</td>
</tr>
<tr>
<td>2012</td>
<td>Lang et al.</td>
<td>Transdisciplinary research in <em>Sustainability Science</em>: Practice, principles, and challenges</td>
<td><em>Sustainability Science</em></td>
<td>73</td>
</tr>
<tr>
<td>2012</td>
<td>Yarime et al.</td>
<td>Establishing <em>Sustainability Science</em> in higher education institutions: Towards an integration of academic development, institutionalization, and stakeholder collaborations</td>
<td><em>Sustainability Science</em></td>
<td>13</td>
</tr>
<tr>
<td>2013</td>
<td>Mauser et al.</td>
<td>Transdisciplinary global change research: The co-creation of knowledge for sustainability</td>
<td>Current Opinion in Environmental Sustainability</td>
<td>14</td>
</tr>
<tr>
<td>2013</td>
<td>Brandt et al.</td>
<td>A review of transdisciplinary research in <em>Sustainability Science</em></td>
<td>Ecological Economics</td>
<td>29</td>
</tr>
<tr>
<td>2013</td>
<td>Cornell et al.</td>
<td>Opening up knowledge systems for better responses to global environmental change</td>
<td>Environmental Science and Policy</td>
<td>13</td>
</tr>
<tr>
<td>2013</td>
<td>Wu</td>
<td>Landscape <em>Sustainability Science</em>: Ecosystem services and human well-being in changing landscapes</td>
<td><em>Landscape Ecology</em></td>
<td>18</td>
</tr>
<tr>
<td>2013</td>
<td>Miller</td>
<td>Constructing <em>Sustainability Science</em>: Emerging perspectives and research trajectories</td>
<td><em>Sustainability Science</em></td>
<td>30</td>
</tr>
<tr>
<td>2014</td>
<td>Miller et al.</td>
<td>The future of <em>Sustainability Science</em>: A solutions-oriented research agenda</td>
<td><em>Sustainability Science</em></td>
<td>35</td>
</tr>
<tr>
<td>2014</td>
<td>Kajikawa et al.</td>
<td><em>Sustainability Science</em>: the changing landscape of sustainability research</td>
<td><em>Sustainability Science</em></td>
<td>15</td>
</tr>
</tbody>
</table>
Figure S2.1 Schematic diagram of the paper sampling in this study. Papers were sampled from Scopus (www.scopus.com) on 03/14/2019, by searching in their titles, abstracts, or keywords via the query of "sustainable development" (SD) and "Sustainability Science" (SS).
APPENDIX B

SUPPLEMENTARY INFORMATION, CHAPTERS 4&5
Table S4.1
Schema for reclassifying land use/cover classes in Liu et al. (2005).

<table>
<thead>
<tr>
<th>Reclassified Category</th>
<th>Original classification</th>
<th>Land use/cover description from Liu et al. 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmland</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paddy land</td>
<td></td>
<td>Cropland that has enough water supply and irrigation facilities for planting paddy rice, lotus etc., including</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rotation land for paddy rice and dry farming crops.</td>
</tr>
<tr>
<td>Dry land</td>
<td></td>
<td>Cropland for cultivation without water supply and irrigating facilities; cropland that has water supply and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>irrigation facilities and planting dry farming crops; cropland planting vegetables; fallow land.</td>
</tr>
<tr>
<td>Industrial, mining, and transportation</td>
<td>Built-up land (others)</td>
<td>Lands used for factories, quarries, mining, oil-field slattern outside cities and lands for special uses such</td>
</tr>
<tr>
<td>land</td>
<td></td>
<td>as transportation and airport.</td>
</tr>
<tr>
<td>Rural settlement</td>
<td>Rural settlements</td>
<td>Lands used for settlements in villages.</td>
</tr>
<tr>
<td>Urban built-up land</td>
<td>Urban built-up</td>
<td>Lands used for urban.</td>
</tr>
<tr>
<td>Sparsely/barely vegetated land</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woods</td>
<td></td>
<td>Lands covered by trees with canopy cover between 10–30%.</td>
</tr>
<tr>
<td>Woodland (others)</td>
<td></td>
<td>Lands such as tea-garden, orchards, groves and nurseries.</td>
</tr>
<tr>
<td>Sparse grass</td>
<td></td>
<td>Grassland with canopy cover between 5% and 20%.</td>
</tr>
<tr>
<td>Permanent ice and snow</td>
<td></td>
<td>Lands covered by perennial snowfields and glaciers.</td>
</tr>
<tr>
<td>Sandy land</td>
<td></td>
<td>Sandy land covered with less than 5% vegetation cover.</td>
</tr>
<tr>
<td>Gobi</td>
<td></td>
<td>Gravel covered land with less than 5% vegetation cover.</td>
</tr>
<tr>
<td>Salina</td>
<td></td>
<td>Lands with salina accumulation and sparse vegetation.</td>
</tr>
<tr>
<td>Bare soil</td>
<td></td>
<td>Bare exposed soil with less than 5% vegetation cover.</td>
</tr>
<tr>
<td>Bare rock</td>
<td></td>
<td>Bare exposed rock with less than 5% vegetation cover.</td>
</tr>
<tr>
<td>Unused land (others)</td>
<td></td>
<td>Other lands such as alpine desert and tundra.</td>
</tr>
<tr>
<td>Densely/moderately vegetated land</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td></td>
<td>Natural or planted forests with canopy cover greater than 30%.</td>
</tr>
<tr>
<td>Shrub</td>
<td></td>
<td>Lands covered by trees less than 2 m high, the canopy cover &gt;40%.</td>
</tr>
<tr>
<td>Dense grass</td>
<td></td>
<td>Grassland with canopy coverage greater than 50%.</td>
</tr>
<tr>
<td>Moderate grass</td>
<td></td>
<td>Grassland with canopy coverage between 20% and 50%.</td>
</tr>
<tr>
<td>Water body</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stream and rivers</td>
<td></td>
<td>Lands covered by rivers including canals.</td>
</tr>
<tr>
<td>Lakes</td>
<td></td>
<td>Lands covered by lakes.</td>
</tr>
<tr>
<td>Reservoir and ponds</td>
<td></td>
<td>Man-made facilities for water reservation.</td>
</tr>
<tr>
<td>Beach and shore</td>
<td></td>
<td>Lands between high tide level and low tide level.</td>
</tr>
<tr>
<td>Bottomland</td>
<td></td>
<td>Lands between normal water level and flood level.</td>
</tr>
<tr>
<td>Swampland</td>
<td></td>
<td>Lands with a permanent mixture of water and herbaceous or woody vegetation that cover extensive areas.</td>
</tr>
</tbody>
</table>