Assessing the performance of ‘comparative agriculture’ methods to determine regional diversity in Australian farming systems

Methodological relevance and application in the Western Australian wheatbelt

Myrtille Lacoste

Masters - Agronomy & Development
B.Sc. Hons. - Plant physiology, Ecology & Evolution

Thesis presented for the degree of Doctor of Philosophy
The University of Western Australia
School of Agriculture and Environment
2017
ABSTRACT

Regional information about the practices, strategies and performances of farmers is necessary to better address agricultural challenges, but is difficult to collect. Comparative agriculture is an integrative discipline which studies farming systems and their diversity holistically through the acquisition of farm information at regional scale. A mixed method procedure is used that cost-effectively collects both qualitative and quantitative data. Despite the recognition that such approaches are necessary to address complex systems and applied problems, comparative agriculture remains unknown in Australia and little used in broadacre systems worldwide. This PhD project determined whether this discipline could make valuable contributions to Australian farming system research.

First, methodological relevance was tested using a broad-scope review. None of the 11 methodological families identified to study farming systems in Australia featured the comparative agriculture procedure, and few similarities were encountered. Furthermore, mixed methods were rarely used (13% of 92 studies).

Second, methodological capabilities were tested with an applied study in the Western Australian wheatbelt. The farming diversity of a 4 000 km² area was assessed using information from 36 farms that represented half the businesses of the area. Six groups were identified which differed across a larger number of characteristics than clusters determined using mainstream multivariate techniques. The iterative nature of the procedure that progressively prioritised the information to be collected was crucial to identify relevant criteria and to ensure data quality.

The performance of comparative agriculture methods was further tested for its ability to establish linkages between farm resources, management and performance. Such linkages are commonly described but rarely confirmed or quantified. Results showed that land types in the study area influenced the regional variability of rotations and farm grain yields, as well as cropping specialisation.

A methodological gap was identified and new information was produced. This included effectively identifying the regional diversity of farming resources, practices, and some of their complex relationships. Practical implications for local research, development and extension are numerous and include improving the design of surveys and field trials, the definition of landscape zones, the parameterisation of farming models, the allocation of investments, and the contents of industry messages. From a broader perspective, this work is also the first comparing the methods of comparative agriculture with mainstream statistical tools.

This PhD project thus demonstrated the value of a discipline that deserves wider application.
ACKNOWLEDGEMENTS

This thesis is the result of 3.5 years of PhD work, enriched by over a decade of prior professional experience and studies in several countries. For this I must first thank the French and Australian tax-payers, governments and varied organisations who funded these efforts, as well as my mother, Catherine Lacoste. Her support, efforts and perseverance in encouraging and allowing me to appreciate both the sciences and humanities have largely contributed to the reasons why I am passionate about the topic of this thesis.

With specific considerations regarding the work presented here I thank the Department of Education and Training of the Australian Government and the Grains Research & Development Corporation of Australia for providing me with a decent scholarship. I am also grateful to all the farmers who contributed their time to the study, the residents of Wyalkatchem for a great window on life in the wheatbelt, and all the researchers and personnel from various institutions who provided help along the way.

This includes my supervisors, whom I thank first for taking on board a “risky” PhD topic, as well as:

• Ken Flower: for being positive, encouraging, and somehow, always available
• Stephen Powles: for being instrumental in helping me to secure good working conditions
• Roger Lawes: for helping me to write better and not shying away from critiques
• Olivier Ducourtieux: for providing his precise, rare expertise in comparative agriculture

Last - because not the least: a PhD is said to be a journey. For me, it was one more step in the luckiest of voyages, the one I have now been sharing with my partner in science and in life, Matthew McNee, for 10 years. Matt is now probably the other person knowing the most about comparative agriculture in Australia, if not the entire southern hemisphere! His agronomic knowledge and his perspective have enriched both my thinking and this thesis. I thank him for his patience, his unfailing support, his enthusiasm, and for sharing the life of our baby Hugo.
I, Myrtille Lacoste, certify that:

This thesis has been substantially accomplished during enrolment in the degree.

This thesis does not contain material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution.

No part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of The University of Western Australia and where applicable, any partner institution responsible for the joint-award of this degree.

This thesis does not contain any material previously published or written by another person, except where due reference has been made in the text.

The work(s) are not in any way a violation or infringement of any copyright, trademark, patent, or other rights whatsoever of any person.

The research involving human data reported in this thesis was assessed and approved by The University of Western Australia Human Research Ethics Committee. Approval #: RA/4/1/6759.

Written participant information was provided and written participant consent has been received and archived for the research involving participant data reported in this thesis.

The work described in this thesis was funded for 3.5 years from July 2013 to December 2016 by:

• The Australian Government, Department of Education and Training through the University of Western Australia (stipend): International Postgraduate Research Scholarship (IPRS), changed to an Australian Postgraduate AWARD (APA) (Ref: 21362065).

• The Grains Research & Development Corporation (top-up stipend and operating costs): Grains Industry Research Scholarship (GRS) (Ref: GRS10566).
This thesis is in agreement with the *Rules for higher degrees by research only, Doctor of Philosophy Rules 10.41(1)* of the University of Western Australia, Australia. It comprises five chapters built around a series of three co-authored scientific articles that were published and/or submitted for publication. The bibliographical details of these publications, where they appear in the thesis and the co-authors contributions are as outlined thereafter:

*Accepted manuscript included as text.*

*Submitted manuscript included as text.*

*Published article included as PDF.*

All the work reported in this thesis is my own, including these three publications (research directions, project design, methods formulation, data collection and analysis, writing). The contributions of the three co-authors are mainly associated with supervisory advice on paper structure through editorial input in various versions of the drafts (e.g. introduction progression, methodological clarifications, discussion details).

---

15th of December 2016

I, Ken Flower, coordinating supervisor, certify that the student statements regarding contribution to each of the works listed above are correct.

16th of December 2016
TABLE OF CONTENTS

Assessing the performance of ‘comparative agriculture’ methods to determine regional diversity in Australian farming systems

Abstract, Acknowledgements, Thesis & Authorship Declaration 1-5

CHAPTER 1. Overall introduction 9
Comparative agriculture, a novel discipline to improve the assessment of regional farming system diversity in broadacre regions

1.1 Research context: Assessing regional diversity as a tool 11
1.2 Methodological gap: Holistic approaches are lacking 12
1.3 Thesis hypothesis: Comparative agriculture can improve assessments 13
1.4 Research objectives: Testing methodological relevance and capability 17
1.5 Thesis structure: Series of 3 journal articles 18
1.6 References 20

CHAPTER 2. Methodological relevance 23
A review of Australian methodologies and approaches to study farming systems

2.1 Preface: new tools are required to achieve holistic reviews
2.1.1 Research context: The difficulty to categorise comparative agriculture 25
2.1.2 Methodological gap: Lack of suitable review procedures 27
2.1.3 Hypothesis: Comparative agriculture has no equivalent in Australian research 28
2.1.4 Research objectives: Drawing a “methodological map” 28
2.1.5 References 29

2.2 Methods to study agricultural systems (article, text)
1. Abstract & Introduction: Broad-scope methodological studies are lacking 30
4. Results & discussion: Methodological approaches, families and groups 37
5. Notes: Strengths and limitations of the interpretative procedure 58
6. Conclusions, Acknowledgements, References 60

2.3 Conclusions: comparative agriculture is relevant 70
CHAPTER 3. Methodological capabilities
Assessing regional farming system diversity in a broadacre region, and comparing performances with mainstream methods (article, text)

1. Abstract & Introduction: Practical challenges of holistic assessments 76
2. Material & methods: The agrarian system & the agrarian diagnosis 79
3. Results: Farming system typology vs. statistical farm clusters 92
4. Discussion: Analytical choices, methodological tools, conceptual originality 105
5. Conclusions, Acknowledgments, References 114

CHAPTER 4. Further methodological capabilities
Linking farming resources, practices and performances (article, PDF)

1. Abstract & Introduction: Lacking information on resources & practices 123
2. Material & methods: Landscape analysis & farmer interviews 125
3. Results: Distinct production practices captured & quantified 128
4. Discussion: New insights about complex farming system relationships 130
5. Conclusions, Acknowledgments, References 135

CHAPTER 5. Overall conclusion
The relevance of comparative agriculture was demonstrated, its performance in assessing regional diversity was validated, and new knowledge about Australian farming systems was produced

5.1 Summary of key findings 141
5.2 Significance of the work and limitations 143
5.3 Future research directions 144
5.4 References 146

Concluding notes 149

All references 151-168
CHAPTER 1

Overall introduction:

Comparative agriculture, a novel discipline to improve the assessment of regional farming system diversity in broadacre regions

1.1 Research context: Assessing regional diversity as a tool
1.2 Methodological gap: Holistic approaches are lacking
1.3 Thesis hypothesis: Comparative agriculture can improve assessments
1.4 Research objectives: Testing methodological relevance and capability
1.5 Thesis structure: Series of 3 journal articles
1.6 References
1.1 Research context: assessing regional diversity as a tool to understand farming systems

Agriculture is the primary food source of a global population counting over 7 billion people. It is a complex, multifaceted industry facing great productive, environmental and social challenges (FAO, 2015). A variety of well-adjusted agricultural policies are required to answer the needs of its myriads of stakeholders, whose diversity represent varied environments and socio-economic situations. This diversity is evident between continents, countries and large regions, but is much more difficult to assess (and address) at local, small regional scales. Farming structures and activities are notoriously variable, even within agricultural regions where conditions appear relatively similar. This includes the wheatbelt of Western Australia where farms vary in terms of sizes, production levels, enterprise mixes, etc. (e.g. Hooper et al., 2011; Planfarm & Bankwest, 2015).

The field of farming system research aims to better understand these variations by studying the numerous and varied components of agriculture together with their interactions. Many objectives in farming system research revolve around identifying the mechanisms that explain the differences observed in farming resources, farmers’ practices and, ultimately, agricultural performances. A typical example includes determining key factors explaining why not all farmers adopt recommended practices.

A variety of methodologies exists, ranging from statistical analyses of farm records, scoping studies using qualitative investigations with farmers, and models that simulate the impacts of given factors on the organisation and outputs of virtual farms (e.g. in Australia: House et al., 2008; Asseng et al., 2010; Greiner & Gregg, 2011; Lawes & Kingwell, 2012; Kingwell et al., 2013; Llewellyn et al., 2014).

Another approach consists in assessing the level and nature of farming diversity using classifications and typologies. These tools are designed to simplify complex situations by categorising farms or farmers into a limited number of categories. The characteristics of these categories are then analysed to determine commonalities and identify relationships.
1.2 Methodological gap: holistic approaches addressing regional diversity are lacking, particularly in broadacre situations

Numerous agricultural classifications and typologies exist and are defined using various criteria for a range of purposes (Emtage & Herbohn, 2012; Kuivanen et al., 2016). However, most examples are either simplistic (i.e. defined using a few criteria, generally arbitrary), or focus on particular farming aspects (van der Ploeg et al., 2009). Holistic approaches that assess farming diversity by considering farming systems as wholes are rare. This is in spite of increasing recognition that holistic approaches are needed to better understand complex, real-world problems such as those that farming system research endeavours to address (Darnhofer et al., 2012; Tonts et al., 2012; Hochman et al., 2013).

One issue particularly hindering holistic assessments of farming diversity is the difficulty of sourcing enough information that is detailed enough, high quality, and representative of the farming population. Current solutions rely on government surveys, targeted studies, private consultant databases, and expert opinions. However, none of these options currently provides the in-depth information required to analyse entire farming systems at regional scales. For instance, data is notoriously scarce with regards to farm resources (e.g. nature and type of land and labour available) and farmers’ practices (e.g. field operations, technologies used, farm-level strategies). Furthermore, current analysis methods seldom consider bio-physical, technical and human aspects jointly. This is particularly the case in data-poor countries, but applies to Australia, Europe and the United States as well. In these countries, detailed agricultural census may be available but these focus on structural, demographic and financial indicators (Iraizoz et al., 2007; van der Ploeg et al., 2009). Farms remain “black boxes” which outputs and inputs can be documented but which internal mechanisms and rationales remain largely unknown.
1.3 Overall thesis hypothesis: comparative agriculture can improve the assessment of regional farming system diversity in broadacre regions

Comparative agriculture is a relatively novel discipline for the holistic study of farming systems, their diversity, and their transformations. Its original framework is based on the concept of agrarian system, that was developed during the 1950s-1980s by French-speaking geographers, agronomists and agricultural economists. By the 1990s, agrarian system approaches were extensively used, in parallel of those carried out in English-speaking farming system research (de Bonneval, 1993; Cochet, 2012). In comparative agriculture, the agrarian system concept is used with a set of mixed methods gathered under the term of agrarian diagnosis. This procedure was designed to acquire large amounts of high quality farm information about a wide range of aspects by cost-effectively collecting both qualitative and quantitative data at relatively small regional scales, mainly through direct observations and farmer interviews (Barral et al., 2012).

In spite of its relevance to current challenges in agricultural research, comparative agriculture remains little known in English-speaking academia (Hervieu, 2012). For instance, the recent book of Darnhofer et al. (2012) that reviewed the varied approaches used in farming system research does not refer to the concept of agrarian systems, but does not mention comparative agriculture.

The multi-disciplinary and mixed methods framework of comparative agriculture was developed in France throughout the 1950s-1980s alongside the concept of agrarian system, was formalised during the last 30 years, and has notably been taught through the FAO and higher education institutions in Paris and Montpellier (FAO, 1999; Barral et al., 2012; Cochet, 2015). In 2012 when background research for this thesis was initiated, the principles of comparative agriculture had been extensively applied by French researchers worldwide. Students from Paris alone had conducted more than 1700 studies in over a hundred countries between 1970 and 2012 (AgroParisTech, 2013). However, only a minority of these were conducted in broadacre contexts, i.e. in regions where farmers practice large-scale crop operations, for instance in Ukraine (Jaubertie et al., 2010), the United States (e.g. Fournier & Simon, 2010), or France (e.g. Dubois, 2010; Cochet et al., 2011; Bordet, 2013). Furthermore, comparative agriculture had only marginally entered English-speaking academia with less than a dozen articles published in international peer-reviewed journals in 8 years (between 2004 and 2012: Cochet, 2004; Ducourtieux et al., 2005; Ducourtieux, 2006; Ducourtieux et al., 2006; Barraud et al., 2008; Aubron et al., 2009; Molnár &
Vandenbroucke, 2010; Cochet, 2011b; Amichi et al., 2012; Moreau et al., 2012). This asymmetry between implementation and publications is not abnormal considering the origins of the discipline: comparative agriculture was not developed by theoreticians in response to conceptual gaps, but by practitioners who needed practical outcomes for agricultural development (e.g. Dufumier, 1996). Surprisingly however, whilst these studies unmistakably applied the methods and concepts of comparative agriculture, only two (those published by Cochet) explicitly mentioned the discipline. Perhaps this was because the synthesis describing the origins and principles of the discipline had only recently been made available and remained in French (Cochet, 2011a), with the exception of one translated chapter (Cochet, 2012).

By the end of 2016 when this thesis was completed, I had identified Springer as a publisher to hasten the availability of a translation (Cochet, 2015, Fig. 1). A handbook describing the methods of the agrarian diagnosis had also been published (Barral et al., 2012), and the number of peer-reviewed publications in English was increasing with a dozen more made available in 3 years (between 2013 and 2016, see list in Table 1). However, examples in broadacre regions were still unavailable, as the unequal geographical distribution of researchers applying comparative agriculture endures (mostly in France, West Africa, Latin America and East Asia). Personal communications with farming system scholars and feedback from varied audiences during presentations in Australia confirmed that comparative agriculture remained unknown, making this thesis all the more relevant.

The hypothesis of this thesis is that comparative agriculture can improve the assessment of regional farming system diversity in Australian broadacre regions, which is tested in Western Australia.

The wider relevance of testing this hypothesis is two-fold. First is to determine the relevance of applying comparative agriculture in all situations worldwide, i.e. not only in developing and European countries where most examples are to be found, but in the broadacre regions of industrialised countries as well. Second is to spread the use of comparative agriculture beyond the French-speaking research community.

Fig. 1. The first synthesis of the discipline of comparative agriculture published in English (Cochet, 2015). This book presents the origins and principles of comparative agriculture, illustrated with studies across the world.
Table 1. Peer-reviewed comparative agriculture studies published in English, 1995-2016.
All below references are journal articles, except conference proceedings (*), book chapters (**), books (***)..

<table>
<thead>
<tr>
<th>References</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>● Essential references</td>
<td></td>
</tr>
<tr>
<td>Concepts (agrarian system) and origin of the discipline</td>
<td>Worldwide</td>
</tr>
<tr>
<td>Methods (agrarian diagnosis) handbook:</td>
<td>Indonesia</td>
</tr>
<tr>
<td>Summary of principles</td>
<td></td>
</tr>
<tr>
<td>A meta-theory of worldwide agriculture using the concepts of comparative agriculture:</td>
<td>Worldwide</td>
</tr>
<tr>
<td>● Studies using the methods of comparative agriculture (agrarian diagnostics)</td>
<td></td>
</tr>
<tr>
<td>Explicit mention of the agrarian diagnosis procedure and/or of the comparative agriculture discipline</td>
<td></td>
</tr>
</tbody>
</table>


---

**Further work building on comparative agriculture results**

Reference only to agrarian diagnostics and/or to the comparative agriculture discipline


1.4 Research objectives: testing the methodological relevance and capability of comparative agriculture in an Australian broadacre situation

The overall objective of this thesis was to determine whether comparative agriculture could make valuable contributions to Australian farming system research, i.e. whether new research practices and/or insights about agricultural issues could be gained from the discipline. This was done by addressing a series of nested objectives, some theoretical, other applied.

One difficulty was to present concepts and to use tools with which the academic and professional agricultural audience was not familiar with. Another challenge was to avoid repeating existing reference material, notably regarding the epistemological basis of comparative agriculture that was extensively developed by Cochet (2015) and references within (origin and scope of the discipline, philosophical and pragmatic foundations, conceptual specificities, comparisons with existing frameworks, validity of the methods notably regarding knowledge acquisition). The thesis achieved this in two parts.

First was to determine the methodological relevance of comparative agriculture, by confirming whether a methodological gap did exist. This implied thoroughly checking whether equivalent procedures to comparative agriculture had been in used in Australian farming system research. To do this, a broad-scope review of the methods used to study agricultural systems was conducted.

A second objective was to empirically assess the methodological capability of comparative agriculture. Beyond theoretical considerations, could the concepts and methods of this discipline indeed contribute new knowledge to Australian farming system research? This question was answered with a field study in a region of Western Australia. The main hypothesis of this thesis was tested by producing a holistic farming system typology to determine in what respects comparative agriculture: (i) was effective to assess regional farming system diversity in broadacre conditions, (ii) performed compared to other methods. After this was investigated whether assessing farming diversity with comparative agriculture could indeed provide new insights about local farming systems. The objective was then to further use the results to establish linkages between farming resources, practices and performances. This was done by analysing landscape information together with farm soils, rotations and grain yields. The usefulness and applicability of such outputs are high and varied, for research (e.g. model parameterisation) and development (e.g. policy design and impact assessment).
1.5 Thesis structure: series of 3 journal articles

As shown in Fig. 2, the research objectives were addressed through three journal articles that can be read either as parts of the whole thesis, or as separate entities (Chapters 2 and Chapter 3 formatted as text, and Chapter 4 formatted as PDF). Each article includes an abstract, introduction, material & methods, results, discussion, conclusion and references sections. This format results in some unavoidable repetitions, especially in the materials and methods sections. In addition, the numbering of sections is discontinuous, and that of the tables and figures is reset at the start of each section (references always apply within the section they are made unless otherwise specified).

As Chapter 1, this overall introduction presented the background and objectives of the thesis. Chapter 2 – Literature review – presents the theoretical study. The corresponding article (section 2.2 Methods to study agricultural systems) is presented between a preface and a conclusion that clarify its contribution to the broader hypothesis addressed by the thesis, and provides the rationale for the review method employed. Chapter 3 – Typology – tests the overall hypothesis of the thesis with an empirical assessment of farming diversity. Chapter 4 – Landscape – further addresses that hypothesis by developing some aspects of the applied work. These two chapters also provide details about the concepts and methods of comparative agriculture, which are therefore only briefly introduced in Chapter 2.

The thesis ends with Chapter 5 as an overall conclusion which draws together key findings to answer the main hypothesis of the thesis, establishes the significance of the work, and highlights areas for further research.
**Fig. 2. Thesis structure.** The thesis addressed several research questions: the main hypothesis was tested in Chapter 3 (typology), was preceded by a theoretical study in Chapter 1 (methodological review), and was further developed in Chapter 4 (landscape analysis).
1.6 References
[except those detailed in Table 1]


CHAPTER 2

Methodological relevance of comparative agriculture:
a review of Australian methodologies and approaches to study farming systems

2.1 Preface: new tools are required to achieve holistic reviews

2.1.1 Research context: The difficulty to categorise comparative agriculture

2.1.2 Methodological gap: Lack of suitable review procedures

2.1.3 Hypothesis: Comparative agriculture has no equivalent in Australian research

2.1.4 Research objectives: Drawing a “methodological map”

2.1.5 References

2.2 Methods to study agricultural systems (article, text)

1. Abstract & Introduction: Broad-scope methodological studies are lacking


3. Material & methods: Interpretative review procedure

4. Results & discussion: Methodological approaches, families and groups

5. Notes: Strengths and limitations of the interpretative procedure

6. Conclusions, Acknowledgements, References

2.3 Conclusions: comparative agriculture is relevant
2.1 Preface: new tools are required to achieve holistic reviews

2.1.1 Research context: the difficulty to categorise comparative agriculture

Testing the methodological relevance of the comparative agriculture to Australian farming system research implied investigating whether similar frameworks had already been in use. The difficulty in answering this question is that the holistic approach of comparative agriculture was constructed using inputs from numerous fields.

As a discipline, comparative agriculture belongs to the social sciences since it studies agriculture as a human activity as opposed, for instance, to experimental agronomy that would only consider bio-physical aspects. Comparative agriculture benefited strongly in that regard from the inputs of geographers, anthropologists, ethnologists, sociologists and even historians, notably to assess the social conditions that ensure the reproduction of political or family structures necessary to explain the organisation of agriculture (Mazoyer & Roudart, 2007; Cochet, 2015). On the other hand, the discipline was built by agronomists trained in economics. As such, comparative agriculture focuses on agronomic mechanisms, technical practicalities and economic relevance, rather than attitudinal and psychological aspects.

Conceptually, the agrarian system shares similarities with the ways farming systems are typically represented in farming system research, with cropping sub-systems at the plot level nested within the whole-farm level (Fig. 1.a). However, the agrarian system also includes regional scales through aspects pertaining to the landscape and, if necessary, to value chains, politics and policies, social relationships (e.g. societal divisions of labour and geographic distribution). The inclusion of socio-political dimensions allows the impact of factors exterior to the farm to be captured, such as the institutional context or historical events. The agrarian system concept thus adds temporal dimensions to spatial considerations. Another reason is to cater for the non-static nature of farming systems that constantly change through time. As such, comparative agriculture is reminiscent of the socio-ecological frameworks that are increasingly used in farming system research as well as other fields such as evolutionary economic geography, environmental history, or political ecology (Boschma & Martin, 2010; Cochet, 2012; Darnhofer et al., 2012; Gautier & Kull, 2015).
Methodologically, the mixed methods of the agrarian diagnosis collect both qualitative and quantitative data. Explorations are essential to the iterative process, with some similarities to grounded theory procedures (e.g., in Australia Eastwood et al., 2012). However, the steps of an agrarian diagnosis are clearly defined (Fig. 1.b). Farmer interviews provide a large part of the information yet a diagnosis is not simply a survey. Instead, it constitutes an entire study where data collection and analysis are largely concurrent. Modelling is an essential part of the exercise but must be anchored in field work and thorough knowledge of the study area.

Evaluating whether equivalent frameworks to comparative agriculture have been in used in Australia thus required a review of methodologies across a wide range of topics and disciplines. No study could be found that established this, in French or in English. Furthermore, no broad-scope review evaluating the use of methodologies could be found in agricultural sciences.

![Fig. 1. Comparative agriculture is an integrative discipline for the holistic study of agricultural situations.](image)

Its primary aim is to inform agricultural development by identifying the practical factors responsible for the farming heterogeneity observed within regions.
This involves determining the level and nature of diversity between farms (e.g. resources, structure, practices, productivities), and the reasons explaining that diversity that may include bio-physical, technical, and human factors. This is done using the concept of the agrarian system and the methods of the agrarian diagnosis.

**The agrarian system (a)** conceptualises agricultural situations using nested scales of analysis, both spatially (field, group of fields, whole-farm, groups of farms, landscape, agricultural region) and temporally (annual and seasonal cycles, technological and societal changes, farm trajectories, agricultural evolution).

**The agrarian diagnosis (b)** is an iterative procedure employing both qualitative and quantitative techniques through several distinct steps. Further details are available in Chapter 3. Applications of comparative agriculture studies include identifying farmer profiles to design conservation projects (e.g. Barnaud et al., 2008), evaluating development projects (e.g. Delarue & Cochet, 2013), parameterising models (e.g. Moreau et al., 2012), determining production factors or practical constrains limiting the adoption of given productions, practices and technologies (Ducourtieux et al., 2006; Aubron et al., 2009; Leauthaud et al., 2013; Aubron et al., 2016; this study, Chapter 4).

### 2.1.2 Methodological gap: no such review conducted before, for lack of suitable procedures

Broad-scope methodological reviews are not normally conducted because of the impracticalities to analyse in details very large bodies of literature.

To solve this issue, a framework employed in health sciences but new in agricultural research was used. Termed an *interpretative review*, this procedure crosses disciplinary boundaries to assess disparate strands of literatures. Here, it was used as a “method to review methods”, capturing methodological details across a wide range of agricultural topics and disciplines. The scope of the literature investigated could have been worldwide but was limited to Australian and New Zealand publications in order to answer the hypothesis of this thesis.
2.1.3 **Hypothesis: comparative agriculture has no equivalent in Australian farming system research**

The hypothesis tested here is that no equivalent to comparative agriculture has been used in Australian farming system research. This is based on:

- the work of [Cochet (2015)](http://example.com) on the origins of comparative agriculture, which emphasised the differences with anglophone approaches and notably farming system research;
- the absence of comparative agriculture in the book by [Darnhofer et al. (2012)](http://example.com) that presented the origin and current status of farming system research (with a focus on Europe but with numerous acknowledgments to Australian connections and contributions);
- the work of [Gautier and Kull (2015)](http://example.com) and [Gautier and Hautdidier (2015)](http://example.com) who pointed out the parallels and differences between French and anglophone schools of thoughts, notably comparative agriculture and political ecology; and
- 8 years of personal experience in Australian academic circles during which no Australian scholar who was aware of the discipline had been encountered.

2.1.4 **Research objectives: drawing a “methodological map” of Australian farming system research**

To answer the hypothesis, the review presented in this chapter aimed at drawing a broad-scope picture of the methods used to study agricultural systems in Australia. More specifically, the research objectives were to:

- identify and characterise methodologies and approaches;
- establish common linkages (e.g. how used and in which typical combinations); and
- identify prominent and marginal approaches by providing some assessment of their relative use by the Australian academic community.

These objectives led to a study conducted over a full year. Paradoxically, comparative agriculture was barely mentioned. The review may thus appear disconnected from the rest of the work presented in the thesis. However, it was necessary to undergo this process not only to learn about methods and to answer the thesis hypothesis, but to provide a thorough background to audiences who may not be familiar with the full methodological range presented here, most of which have some relevance to comparative agriculture.
2.1.5 References


2.2 Methods to study agricultural systems

This section reproduces verbatim the article accepted for publication in Sustainable Agriculture Reviews on the 9th of August 2016.

Myrtille Lacoste, Roger Lawes, Olivier Ducourtieux and Ken Flower

Abstract Modern agriculture faces varied, complex and ever-evolving challenges. Productive, environmental and social requirements are to be met while fulfilling the needs of numerous stakeholders across a wide array of conditions. To better meet these challenges, researchers study agricultural systems using a myriad of methods, across varied disciplines and contexts. To help connect and orientate these research efforts, an overview is required that assesses and categorizes the diversity of approaches and methodologies being used to study agricultural systems. Whilst a plethora of specialized studies are available, broad-scope methodological reviews are lacking. The difficulty resides in integrating very different research practices and varied strands of literature to encompass the many fields and disciplines relevant to the study of agricultural systems.

Such a multi-disciplinary review is provided here for the methods used in Australia and New Zealand, to study farms, farmers and their broader environment. Both quantitative and qualitative studies were included across a particularly wide range of publications while retaining a high level of methodological detail. An original overarching framework was produced that coherently summarized, described and categorized the diversity of methods encountered. This included defining classification criteria that can be conveniently applied to compare methods, assess their relative use, and identify linkages between approaches (common combinations and similarities in terms of underlying principles).

To achieve this, an interpretative approach was employed that is novel in agricultural sciences. Ninety-two publications from a diverse pool of 400 items were reviewed in detail, a majority of which published internationally in peer-reviewed journals during 2004-2014. Three overarching approaches were identified, with
publications focusing on “characterizing agricultural situations” (64%), “identifying relationships” (59%), and/or “retracing processes” (42%). A total of 28 method groups were identified, clustered in 11 broader methodological families that ranged from simple indicators, statistics and narratives to elaborate participatory research, system modelling and mathematical programming.

These categories were used to appraise Australian methodological practices. This included highlighting the connectivity between the high number of quantitative methods encountered (used by 72% publications) and their usually clear, well-established protocols. In contrast, qualitative studies (41%) frequently suffered from inconsistent terminologies and demonstrated a lower diversity of methods in use. The review also noted that details and justifications about descriptive methods were often neglected, in spite of their impact on the entire analysis process. In addition, relatively few studies made use of long-term historical information to generate new knowledge and insights about future directions. Mixed methods were little used (only 13% of publications), as well as some frameworks including those pertaining to social-ecological systems, agrarian systems or evolutionary economic geography.

Overall, these results show that agricultural research in Australia remains highly quantitatively oriented, favoring analytical details over data origin, and eclipsing a range of qualitative methods and emerging frameworks. Enduring disciplinary and topical divides (notably social/technical), lack of awareness and of expertise are likely explanations. To remedy this, under-used methods would benefit from being proactively promoted and taught, and from concerted efforts to build shared, stable nomenclatures about meanings and protocols. Better documentation of data sources is also required.

**Keywords** Interpretive synthesis • Literature review • Multi-disciplinary • Research practice • Mixed methods • Farming systems • Farmers • Rural processes

---

M. Lacoste • K. Flower
The University of Western Australia, School of Plant Biology, Crawley, WA 6009, Australia
email: myrtille.lacoste@gmail.com

R. Lawes
CSIRO Ecosystems Environment, Floreat, WA 6014, Australia

O. Ducourtieux
AgroParisTech, UFR Comparative Agriculture, UMR PRODIG, 75231 Paris Cedex 05, France
1. Introduction

As with most research fields, the study of agriculture nowadays benefits from the input of numerous disciplines. Overarching assessments of this large body of literature are required to inform and improve research practices. To date, however, such characterizations remain rare (Cañas-Guerrero et al., 2013). Specifically, there is a paucity of broad-scope studies categorizing the myriad of methods employed by the research community when addressing problems at the rural, farm, and farmer scales (Fig. 1). The objective of this study was to provide such a broad-scope, multi-disciplinary methodological review, that was relevant and accessible to a wide audience across the agricultural research community.

Whilst specialized methodological reviews are routinely conducted in agricultural system research, attempts at comparing approaches across the many relevant fields and disciplines are hindered by practical issues. The difficulty resides in integrating very different methodologies from varied strands of literature. Particularly challenging is to assess jointly both quantitative and qualitative contributions, and bridging both technical and social sciences. These issues were addressed here by using an “interpretative” type of review. This novel procedure, unlike commonly used “systematic” reviews, is able to encompass varied types of research in order to provide a broad-scope, integrated overview of the approaches and methodologies used to study farms, farmers and the broader agricultural environment.

The interpretative review procedure was applied to Australian research, inclusive of New-Zealand. Relevance to the global sphere and the study of agricultural sustainability was ensured with a majority of publications published internationally, and with the breadth of topics covered that was purposively kept as broad as possible. Outputs include an overarching methodological framework and classification criteria that can be used as references to identify research practices across varied fields. The value of categorizing methodologies and approaches includes aiding the critical appraisal of research practices, as well as the search and selection of tools to orient future research and the design of sustainable systems. This involves identifying mainstream methods with their advantages and pitfalls, and conversely, recognizing promising emergent methods seldom acknowledged due to the smaller size of the communities employing them. Documenting methodological perspectives is also meant to foster dialogue between fields. Specific goals include increasing transdisciplinary collaboration and the use of mixed methods, which are both increasingly recognized as necessary to adequately study complex agricultural systems and address real-world societal problems (Tashakkori & Teddlie, 2010; Simon & Schiemer, 2015). Other
applications include comparing the research practices of given communities (e.g. disciplines, countries, institutions), and monitoring the evolution of school of thoughts together with their practical applications (e.g. Gautier & Hautdidier, 2015).

The paper is organized as follows. First, an overview of review procedures is provided to justify the approach used in this study. The review protocol used is then described. An overview of the resulting methodological classification follows, prior to describing each category in more details. This allowed appreciating the range and diversity of methods encountered, contrasting methodological nuances, detecting common relationships, and identifying emerging tools. Lastly, as recommended by Dixon-Woods et al. (2006b), a reflexive account of trialing an interpretive type of review is provided. Strengths and weaknesses of the procedure and of its outputs are discussed, with the aim of allowing others to learn about and improve on a type of review that is not yet formalized in agricultural research.

Fig. 1. Diversity of methods in agricultural system research: scales, topics, disciplines. The study of agricultural systems can be undertaken at various scales through a myriad of methods. For instance in the broadacre crop-livestock systems of Western Australia, varied examples include: rural and farm studies at the landscape scale (e.g. a: organization of lupin, wheat and canola fields across heterogeneous soils); bio-physical monitoring of productive attributes (e.g. b: weather station and machinery yield-mapping in wheat field at harvest); participatory evaluation with farmers (e.g. c: feedback on farming system economics).


A plethora of methodological reviews are available that evaluate the relevance, applicability and contribution of various methods, tools and their conceptual basis to the current state of knowledge (e.g. Reed et al., 2009; Renting et al., 2009). Closer to the object of this study are the reviews that specifically assess the extent to which these methods are actually applied by academic communities. Objectives include assessing
the current research situation, monitoring change, and evaluating discrepancies between what is recommended and what is used. In agricultural sciences, the vast majority of these reviews are conducted according to “systematic” frameworks. However, this framework is unsuitable for use here, as discussed hereafter.

2.1 Systematic Reviews

Systematic review frameworks involve the exhaustive inclusion of all relevant publications following an explicit protocol. The corresponding ‘complete’ pool of items, that may be characterized as a whole, sampled or downsized, allows describing statistically the distribution of publications. Most systematic techniques make use of the standardized bibliometric information compiled by academic databases. Broad-scale examples include Cañas-Guerrero et al. (2013), Bravo-Vinaja and Sanz-Casado (2008), and in Australia Pratley (2015). In these studies, international and national agricultural research activities were characterised and monitored using year impact factors, number of collaborators, research institutions, and other similar indicators combined with keywords. However, the impracticalities of indexing in-depth article information hinder other bibliometric descriptions of the literature. For instance, Brym and Reeve (2016) performed a systematic review on terminologies but reduced their sample to ten items in order to adequately developed their commentaries. Addressing methodological details over a vast number of publications is similarly unfeasible. Crucially, systematic reviews often exclude qualitative studies altogether are these are inconsistently referenced in databases (Dixon-Woods et al., 2006a). For the same reason, grey literature is rarely included either.

To remedy these issues, other studies employ data-mining techniques combined with participatory approaches which allow the definition of more endogenous and relevant criteria (e.g. Barbier et al., 2012). However, even with the contribution of academics who are experienced with varied nomenclatures, automated procedures reach their limits when content cannot be parted from context in order to make sense. Keywords can be useful proxies, but only careful reading can dissect the correct meanings associated with complex concepts, evolving vocabulary and ill-defined terminologies (e.g. terms that are: widely employed but particularly polymorph such as “interviews”, “survey”, “models” or “participatory”; ambiguous and malleable such as “resilience”; bearing multiple definitions and usages such as “agroecology” (Reed et al., 2009; Reid & Botterill, 2013; Brym & Reeve, 2016). As a result, the more detailed the study, the smaller the corpus covered. Methodological reviews are complex and thus generally downsized to manageable levels by answering focused questions within restricted scopes. Examples include reviewing a given method within a given set of academic journals (e.g. whole-farm models, Robertson et al. (2012b); quantitative
meta-analysis Philibert et al. (2012)), or a conceptual approach and its applications within a topic and/or sub-discipline (e.g. systems approaches to innovation in crop protection, Schut et al. (2014); life cycle assessment in aquaculture Henriksson et al. (2011)). Whilst suitable for the detailed assessments of restricted methodological topics, systematic reviews are thus impractical for the goals of this review that also require accessing a high level of detail, but are purposively broad-scope. Consequently, an interpretive type of review was used instead.

2.2 Interpretative Reviews
Interpretative reviews specifically aim at combining heterogeneous sources and connecting segments of the literature that are methodologically different. The approach, extensively described by Dixon-Woods et al. (2006a; 2006b), is based on the iterative analysis of manually selected items until theoretical saturation is reached, i.e. when no new information is encountered. Whilst searching strategies and categorization criteria are explicit and pre-specified in systematic reviews, in interpretative reviews they are shaped progressively with each retrieved item. Instead of precisely defined research questions, queries are purposively flexible in order to cross disciplinary boundaries. The transparency and reproducibility requirements upheld by systematic procedures are thus not necessarily claimed by interpretive reviews. In fact, like most topical reviews, producing a concise account of disparate literature strands implies a certain degree of subjectivity. Evidently, this is counterbalanced by evidence and reflexivity.

Interpretive review procedures have gained popularity in various health-related research fields (Morrison et al., 2012; e.g. Moat et al., 2013), largely for their potential to synthesize both quantitative and qualitative evidence (Suri & Clarke, 2009). No such use of the approach could be found in agricultural research. Review procedures featuring similarities exist but scopes remain focused, rendering the thought process involved relatively self-explanatory and diminishing the explicit need for theoretical saturation. Examples includes Le Gal et al. (2011) and Pearson et al. (2011) whose methodological classifications were the results of the researchers’ own informed understanding, based on publications selected manually.

Lastly, it should be mentioned that other types of reviews exist which specifically aim at combining heterogeneous sources and connecting segments of the literature that are methodologically different (Suri & Clarke, 2009). Among them is the meta-narrative of Greenhalgh et al. (2005), illustrated on the topic of food security by Weiler et al. (2015). The review process described hereafter was retained for the possibility to cover a particularly broad scope in a cost-effective manner.

The review process was conducted in 2014 in three stages. The selection of relevant publications started using Google Scholar. This source of publications was chosen over the more traditional Web of Science or Scopus databases because of its academic and topical comprehensiveness, ability to access varied material, and importantly, convenience of use (Harzing, 2012; Lasda Bergman, 2012). This facilitated the broad-scope search and the inclusion of a range of documents readily accessible to non-academics such as conference papers and reports. “Popular” publications most cited and likely to be used were targeted, i.e. those appearing at the top of search results ranked by “relevance”. This ranking criteria integrates contents, location, authors, citation dates and frequency (Google, 2015). Multiple searches were performed with various combinations of broad-spectrum keywords such as “Australia”, “farmer”, “farming systems”, “rural”, “agricultural practices”, “analysis” “methods”, etc. Searches were initially centered on the broadacre sector of Western Australia, but re-run to include others industries across Australia. New Zealand was also included, for the similarities and linkages shared by the two countries’ research communities. Publications were selected by rapidly screening their title and header. Besides a 10-year publication date limit, inclusion criteria were (i) a majority of authors affiliated to an Australian or New Zealander institution, (ii) addressing aspects of what farmers do, and (iii) demonstrating some farm-level or broader scale considerations. These last two criteria remained purposively imprecise, resulting in a wide range of disciplines and topics being included about both existing agricultural systems and virtual representations, the people implementing these systems and their interactions with the broader environment at various scales, as well as the wider contexts in which farming can be understood such as value chains, natural resource management, and rural governance. Studies purely furthering knowledge on biological mechanisms were excluded, unless the paper objectives clearly addressed management issues or other farming system aspects. A pool of 400 publications was thus manually compiled.

The second stage involved randomly retrieving publications from this pool which were read in-depth and organized according to three hierarchical levels of categorization, or discarded if appearing out of topic. First, papers were assigned to one or several “method groups” featuring similar tools and techniques that constituted the base unit of the categorization. When significantly overlapping and sharing comparable underlying principles, method groups were clustered to form a higher categorization level named “methodological families”. These were in turn grouped into “overarching approaches” according to the general type of information pursued to address the
research question. An iterative process to identify patterns was used, during which the criteria discriminating each group were progressively refined to accommodate new information. Method groups, methodological families and overarching approaches were thus defined interpretatively throughout the analysis procedure, sometimes merged or split. A situation of saturation at which point no new group could be identified was reached after retrieving 192 publications, from which 82 were retained and classified.

The third stage brought 10 non-random contributions to the sample. These were added primarily to populate method groups that featured too few items, as some types of studies were much rarer than others and thus too rarely encountered using random selection. These non-random contributions were sourced from the pool, from references cited in retrieved publications, and from the authors’ own libraries.

Results were summarized into a “method map”, i.e. a schematic showing all the categories identified, their hierarchy and common linkages. A network graph was also produced with R using methodological families as nodes (Fruchterman-Reingold layout, seed = 14, Csardi and Nepusz (2006); R Core Team (2015)). The relative importance of each methodological family in the sample was represented through the size of the nodes, based on an index summing the number of times each method group was used, weighted by their importance within each publication (companion method group = 1 point, core analytic method group = 5 points). All the links between methodological families existing within each publication were included (e.g. a publication using 4 methodological families produced 6 links; 2 families, 1 link; 1 family, 1 looped link). Finally, an a posteriori measure of network modularity using qualitative and quantitative divisions was calculated, to assess whether the two types of research formed distinct communities within the network.

4. Results and Discussion: Overarching Approaches, Methodological Families, Method Groups

A total of 92 publications were retained for analysis, with 89% sourced randomly. Peer-reviewed journal articles represented over two thirds of items, with grey literature also well represented (Fig. 2). The analysis resulted in the identification of 28 “method groups” that were clustered in 11 “methodological families” and 3 “overarching approaches” (Fig. 3). The “method map” (Fig. 3a) shows the diversity of method groups encountered, an appraisal of how frequently they were used, and how they were most often combined. Although necessarily simplified, this visual representation of a complex research situation allows for an overall perspective of the common
relationships between methodological families and their relative positioning within overarching approaches in terms of underlying principles. The actual number of publications on which each category was based is provided in Table 1 and in the descriptions thereafter, e.g. [20/9] which shows first the total number of publications where the method was encountered, followed by the number of cases where it constituted a core analytic method. Many publications are double-counted as they are legitimately placed in several categories simultaneously. The complete list is available from the authors.

The network graph (Fig. 3.b), built on a total of 432 links, completes the method map with an automated visualization of the relationships between methodological families. Whilst the method map aims at synthetic clarity, the network graph captures other aspects of the sample such as connectivity structure (proximity of families), connectivity strength (density of connections), and modularity (denser connections within qualitative and quantitative groups of methodological families).

![Table 1](image)

<table>
<thead>
<tr>
<th>Publication type</th>
<th>13%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Articles, Aust./NZ</td>
<td></td>
</tr>
<tr>
<td>Articles, international</td>
<td>55%</td>
</tr>
<tr>
<td>Conference proceedings</td>
<td>5%</td>
</tr>
<tr>
<td>Book chapters</td>
<td>5%</td>
</tr>
<tr>
<td>Reports</td>
<td>21%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Publication dates</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of authors</td>
<td>15%</td>
<td>54%</td>
<td>30%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main orientation</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agronomy</td>
<td></td>
</tr>
<tr>
<td>Economics</td>
<td>24%</td>
</tr>
<tr>
<td>Natural resources</td>
<td>8%</td>
</tr>
<tr>
<td>Rural sociology</td>
<td>35%</td>
</tr>
<tr>
<td>Benchmark surveys</td>
<td>9%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main type of analysis</th>
<th>59%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantitative</td>
<td></td>
</tr>
<tr>
<td>Qualitative</td>
<td>28%</td>
</tr>
<tr>
<td>Both employed</td>
<td>13%</td>
</tr>
</tbody>
</table>

Type and location of the studied industries

<table>
<thead>
<tr>
<th>Crops &amp; livestock (mainly rainfed in Southern zone: )</th>
<th>54%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy</td>
<td>9%</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>9%</td>
</tr>
<tr>
<td>Horticulture and arboriculture</td>
<td>4%</td>
</tr>
<tr>
<td>Value chains</td>
<td>4%</td>
</tr>
<tr>
<td>Other / several industries</td>
<td>20%</td>
</tr>
</tbody>
</table>

**Fig. 2. Characteristics of the review sample.** Total number of publications included: 92, of which 82 were retained out of 192 retrieved randomly from a pool of 400 sourced from Google Scholar, discarding 110 out-of-topic items. An additional 10 publications were added non-randomly. The sample size was determined by theoretical saturation i.e. when no new information is encountered (interpretative review procedure).
Prior to detailing the methodological categories, some of the terms employed and limitations to this type of representation should be clarified. Generally, it should be remembered that the actual diversity and complexity of methods and their uses are naturally richer than the simplified picture provided by an organized grouping.

First, methods crossed boundaries. Consequently, some make more sense when considered in a broader context than that of a “methodological family”. This is notably the case of qualitative methods that may produce both quantitative and qualitative information, and often corroborate evidences in a triangulation process (e.g. Kalaugher et al., 2013; Rodriguez et al., 2014). Similarly, overarching approaches can easily overlap. The objective of an analysis can be both to “characterize a situation” and “identify relationships”, which sometimes involve “retracing processes”. Most publications, however, present results focused on one or two of these aspects through a “core” method, the others being inferred in discussions, or addressed by companion procedures. Sometimes, this occurs because studies are purposively split in more or less complementary articles submitted to different journals, each focusing on different sets of results and corresponding methods.

Second, methods can be applied in slightly different ways for very different objectives. For instance, data reduction methods can be used to segregate a sample (“data-mining”) and to establish relationships between variables (“confirmatory statistics”). Incidentally, this example shows that deductive/inductive types of reasoning do not always match the quantitative/qualitative type of data analysis they are frequently attributed to.

Third, different methods can be hidden behind similar or ill-defined terminologies. Efforts were made to match existing discipline-specific vocabulary, however this was not always possible. The names attributed to each method category were tailored to best convey results to a wide, non-specialist audience. For instance, the term “content analysis” was applied to a category broader than practitioners may commonly refer to, for similarities in principles rather than for commonalities in software or material. To facilitate reading, italic fonts are used to highlight that nomenclature, as well as the core criteria upon which the categories were built.

The next three sections, one for each overarching approach, describe the categories and some of their relationships. Differentiating criteria and common topics are highlighted along with typical examples. Mainstream and emerging methods are pointed out, and finally issues frequently encountered during the classification process.
Fig. 3. A classification of methods to study agricultural systems. The review results were synthetized in the method map (a) that shows the 3 hierarchical levels retained (“method groups”, within “methodological families”, within “overarching approaches”). This simplified representation of the myriad of methods encountered also summarizes relative frequencies and common relationships in the Australian context, i.e. similarities in underlying principles, and how methods were found in the sample to be commonly employed concurrently in order to complement each other. The network graph (b) is an alternate, computer generated
visualization that complements the method map. The position of each methodological family (nodes) and the density of linkages corroborate the descriptions detailed in sections X.4.1-X.4.3: central position and importance (size of node) of “indicators” which are rarely used as core analytic methods but are ubiquitous (overlapping all three overarching approaches, represented in green); importance of “system modelling” for which the opposite applies; dominance and close connectivity of the quantitative methods of the second approach (darkest green); high connectivity of “content analysis” and “narratives”; remoteness and small size of “reconstitutions”; divide between quantitative (blue) and qualitative (yellow) research, confirmed visually (qualitative methods confined to the network periphery) and by a positive modularity of 0.38 (denser connections exist within each research type than overall). Interestingly, “participatory research” is the qualitative family best connected to quantitative methods, notably to “system modelling” and “coding”: when added to the quantitative research group, modularity increases to 0.45.

Table 1. A classification of methods to study agricultural systems with published Australian and New Zealand examples. A total of 28 method groups were identified, clustered in 11 methodological families (light grey) and 3 overarching approaches (dark grey). The number of publications on which the description of each category was based is provided. The number of publications (in parenthesis) for which it is the main or core method used, i.e. the method(s) on which emphasis is put to perform the analysis and produce results. Many publications are double-counted as they are legitimately placed in several categories simultaneously. The entire list of publications and their attributions to categories is available from the authors.

<table>
<thead>
<tr>
<th>CHARACTERISING CURRENT SITUATIONS (APPROACH 1)</th>
<th>92 (59)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indicators</td>
<td>84 (16)</td>
</tr>
<tr>
<td>Summary statistics</td>
<td>64 (16)</td>
</tr>
<tr>
<td>e.g. means, ranges, standard variations, frequencies, histograms (Wheeler et al., 2013)</td>
<td></td>
</tr>
<tr>
<td>Key attributes</td>
<td>34 (7)</td>
</tr>
<tr>
<td>e.g. characteristics of farm case studies (Ransom &amp; Trapnell, 2011), values of representative systems (Biggs et al., 2013)</td>
<td></td>
</tr>
<tr>
<td>Visual tools</td>
<td>20 (8)</td>
</tr>
<tr>
<td>e.g. relative mapping (Cary &amp; Roberts, 2011), bubble plots (Stott et al., 2013), cluster maps (Kingwell et al., 2013), schematics (Raymond &amp; Robinson, 2013)</td>
<td></td>
</tr>
<tr>
<td>Coding</td>
<td>24 (8)</td>
</tr>
<tr>
<td>Scoring/rating</td>
<td>19 (5)</td>
</tr>
<tr>
<td>e.g. Likert scales (Raymond &amp; Spoehr, 2013), scores/weights (Price &amp; Leviston, 2014), ranking adaptive index (Wheeler et al., 2013)</td>
<td></td>
</tr>
</tbody>
</table>
### Other rules
- Categorisation ([Cary & Roberts, 2011](#)); binary statements ([Llewellyn et al., 2012](#)); digital mapping ([Welsch et al., 2014](#))

### Segregating
19 (9)
- Categorising with factors e.g. dominant enterprises ([Sheng et al., 2011](#)), soil types ([Robertson et al., 2009](#)); segmenting with continuous variable e.g. operating profit per hectare ([Browne et al., 2013](#)), input and output levels ([Stott et al., 2013](#))
- E.g. grouping statistics incl. cluster analysis ([Sherren et al., 2011](#)); spatial algorithms ([Zerger et al., 2011](#)) and mapping rules ([van Gool, 2011](#))

### Content analysis
24 (23)
- Coded themes: e.g. cross-case analysis and hierarchical nodes coding ([Broderick et al., 2011](#)), open coding ([Raymond & Robinson, 2013](#)), manual coding ([Moon, 2013](#))
- Exploration (iteration): e.g. repeated interviews ([Gill, 2011](#)), reaching saturation ([McKenzie, 2013](#)), alternating individual data analysis and group discussions ([Cheshire et al., 2013](#))
- Compilations: commented summary of answers ([McConnell, 2011](#))

### Participatory research
16 (12)
- Collaborative (consensus): e.g. participatory modelling ([Rodriguez et al., 2014](#)), steering committee ([Armstrong et al., 2010](#))
- Elicitative (focus groups): e.g. standard ([Cary & Roberts, 2011](#)) or computer-based ([Islam et al., 2006](#)) focus groups, workshops ([Roebeling & Webster, 2007](#))
- Consultative (step-wise process): e.g. Mixed Methods Framework ([Kalaugher et al., 2013](#)), Multi-Criteria Assessment ([Zerger et al., 2011](#))

### Identifying relationships (Approach 2)
59 (54)

### Confirmatory statistics
34 (21)
- Standard statistical tests & correlations analysis: e.g. $\chi^2$ ([Weller et al., 2013](#)), t-tests ([Llewellyn et al., 2012](#)), analysis of variance ([Entage & Herbohn, 2012](#)), z-score ([Wheeler et al., 2012](#)), rank order correlations ([Greiner & Gregg, 2011](#))
- Statistical models: e.g. multiple linear regression ([Christie et al., 2011](#)), Ordinary Least Squares ([Llewellyn & Pannell, 2009](#)), mixed models ([Lawes & Kingwell, 2012](#)), logit ([D'Emden et al., 2008](#)), probit ([Nossal & Lim, 2011](#))
<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data reduction methods</td>
<td>e.g. Factor Analysis (<a href="#">Rodriguez et al., 2014</a>), Principal Component Analysis (<a href="#">Greiner &amp; Gregg, 2011</a>)</td>
<td>7 (3)</td>
</tr>
<tr>
<td>Causal models (path analysis)</td>
<td>Structural Equation Modelling (SEM) (<a href="#">Price &amp; Leviston, 2014</a>)</td>
<td>3 (3)</td>
</tr>
<tr>
<td><strong>Mathematical programming</strong></td>
<td></td>
<td>23 (22)</td>
</tr>
<tr>
<td>Efficiency and utility analysis</td>
<td>e.g. Total Factor Productivity indexes and Data Envelopment Analysis (<a href="#">O'Donnell, 2010</a>), stochastic distance functions (<a href="#">Cattle &amp; White, 2007</a>); Duration analysis (<a href="#">D'Emden et al., 2008</a>)</td>
<td>12 (11)</td>
</tr>
<tr>
<td>Optimisation</td>
<td>e.g. maximising response function (<a href="#">Lawes &amp; Robertson, 2011</a>), mean-variance models (<a href="#">Komarek &amp; MacAulay, 2013</a>), linear programming incl. MIDAS model (<a href="#">Bell et al., 2008</a>)</td>
<td>13 (13)</td>
</tr>
<tr>
<td><strong>System modelling</strong></td>
<td></td>
<td>29 (27)</td>
</tr>
<tr>
<td>Simulators</td>
<td>e.g. field-scale crop production incl. APSIM with yield prediction (<a href="#">Kirkegaard &amp; Hunt, 2010</a>) and environmental impacts (<a href="#">Thorburn et al., 2010</a>); pasture production systems (<a href="#">Browne et al., 2012</a>); regional production (<a href="#">van Gool, 2011</a>)</td>
<td>13 (12)</td>
</tr>
<tr>
<td>Organisers</td>
<td>e.g. field operations (<a href="#">Webster et al., 2009</a>), crop sequences (<a href="#">Lawes &amp; Renton, 2010</a>); whole-farm resource allocation incl. MIDAS (<a href="#">Bell et al., 2008</a>); whole-farm management rules (<a href="#">Rodriguez et al., 2014</a>)</td>
<td>12 (12)</td>
</tr>
<tr>
<td>Calculators</td>
<td>e.g. nutrient requirements (<a href="#">Lawes &amp; Robertson, 2011</a>); greenhouse gas emissions (<a href="#">Christie et al., 2011</a>); cost-benefit analysis (<a href="#">Bell et al., 2008</a>); annual whole farm budgets (<a href="#">van Grieken et al., 2010</a>); sensitivity analysis (<a href="#">Monjarino et al., 2010</a>); Monte Carlo simulations (<a href="#">Heard &amp; Leddin, 2012</a>)</td>
<td>23 (18)</td>
</tr>
<tr>
<td><strong>RECONSTITUTING PAST MECHANISMS (APPROACH 3)</strong></td>
<td></td>
<td>45 (39)</td>
</tr>
<tr>
<td>Time series</td>
<td></td>
<td>32 (22)</td>
</tr>
<tr>
<td>Patterns</td>
<td>e.g. trends and conjunctures (<a href="#">Kingwell &amp; Pannell, 2008</a>); standard patterns (<a href="#">Llewellyn et al., 2012</a>); comparative demographics (<a href="#">Stewart et al., 2011a</a>)</td>
<td>25 (11)</td>
</tr>
<tr>
<td>Mathematical and statistical models</td>
<td>e.g. production function (<a href="#">Sheng et al., 2011</a>); distance function (<a href="#">Villano et al., 2010</a>); duration analysis (<a href="#">D'Emden et al., 2006</a>); longitudinal regression (<a href="#">Lawes &amp; Kingwell, 2012</a>)</td>
<td>17 (15)</td>
</tr>
<tr>
<td>Narratives</td>
<td></td>
<td>20 (17)</td>
</tr>
<tr>
<td>Individuals (case studies)</td>
<td>e.g. personal records (<a href="#">Stewart et al., 2011b</a>); in-depth interviews (<a href="#">Ransom, 2011</a>); exploratory longitudinal (<a href="#">Eastwood et al., 2012</a>); content analysis methods</td>
<td>7 (7)</td>
</tr>
</tbody>
</table>

43
4.1 Characterizing Situations: Focus on Describing the Object of Study

The first overarching approach [92/59] comprises methods that describe what is present, be it a group of fields, farms, farmers, management practices, agro-ecosystems, or a region encompassing all the above. All 92 publications used descriptions that most often represented simple analytic pre-requisites, capturing what is done, owned or thought, by whom, where and when, in order to provide material for the methods of the second and third approaches. Characterizations can also constitute a core analytic tool themselves, providing explanatory results by exposing critical information, pointing out evidence, comparing results and building hierarchies.

Although the act of describing may seem a straightforward activity, a large variety of methods was encountered. These methods were organized into five methodological families (Fig. 3). Three involved tools that compiled data in quantitative formats: “indicators”, “coding”, “segregating”. Two involved qualitative procedures: “content analysis” and “participatory research”.

• “Indicators” [84/16]. This methodological family comprises the simplest tools available to explore, assess and compare given characteristics. Indicators are primarily used as introductory or accompanying tools which simply describe the information at different stages of the analysis. The main instance where indicators are truly central to studies is benchmarking, i.e. the collection of a critical number of observations compiled to provide standards for a population. Examples range from national to local surveys that address, mostly, farm standard characteristics and performances at farm or field level (Nossal & Lim, 2011; Browne et al., 2013; Planfarm & Bankwest, 2013). A similar exercise consists in characterizing specific aspects of a population, for instance technology adoption status (Llewellyn et al., 2012), awareness levels (Watson & Watson, 2013), farmers perceptions toward land management issues (Sherren et al., 2011), etc. Three method groups were distinguished.
The most common are the well-known “summary statistics” [64/16], also called “descriptive statistics” (averages, variance, distributions etc.) that gauge samples and present results. They are not necessarily followed by statistical tests.

Indicators can be reduced to “key attributes” [34/7], typically farm structure, productivity and profitability characteristics. These features, completed or not by descriptors, are most often encountered when the sample is small or when the analysis dissects a given farm, real or virtual (Armstrong et al., 2010; Ransom & Trapnell, 2011; Biggs et al., 2013)

The third method group is composed of “visual tools” [20/8]. The idea is not necessarily to fit a statistical trend line but to allow for a more manual analysis of the observations, for instance to appraise the cope of differences. Examples include: mapping the relative private and public benefits of farm practices for environmental management (Cary & Roberts, 2011); prioritizing research on best management practices (Roebeling & Webster, 2007); comparing production with bubble plots (Stott et al., 2013); representing farm similarities with cluster maps (Kingwell et al., 2013); obtaining benchmark frontiers by hand-fitting curves on modelled data (Kingwell, 2011); graphically represent mathematical solutions (Komarek & MacAulay, 2013). Schematics were also included when crucial to the representation, interpretation and discussion of results (Oro & Pritchard, 2010; Raymond & Robinson, 2013; Rodriguez et al., 2014).

- “Coding” [24/8]. This process involves transforming qualitative information into numerical variables. Numbers and categories are attributed to specific types of answers, often building indexes, following rules that are either pre-decided or which definition is part of the analytic process. Typically, coding allows inputting farmers’ attitudes, perceptions and other psychological and behavioral traits into quantitative analysis methods (Price & Leviston, 2014). Another case is the translation of spatial information into numerical datasets. Welsch et al. (2014) provided detailed examples of both situations.

“Scoring scales” [19/5], which produce semi-continuous variables, were found to be the most common method used in coding, particularly 1-to-5 Likert type scales (Raymond & Spoehr, 2013).

A variety of “other rules” [9/5] exist. For instance, Nossal and Lim (2011) built a measure of farmers’ innovative efforts based on the number and extent of innovations that each grower had adopted, whilst Cary and Roberts (2011) and Price and Leviston (2014) both scored environmental land management practices using iterative processes.
• “Segregating” [19/9]. This type of procedure consists of dividing the sample to be worked with into groups, rather than addressing the information pool as a whole.

The most frequent procedure is to “partition” [14/6] the sample according to pre-set criteria, generating classes for which descriptive statistics are then provided. Typically, partitioning is applied to census and benchmark data. The most common partition criterion is probably farm enterprise, assessed through either production outputs or land use. For instance, the Australian national farming surveys divide broadacre farms into cropping specialists, mixed crop-livestock, sheep specialists, beef specialists and mixed sheep-beef (Sheng et al., 2011). Classes can also be created by segmenting a continuous variable using quartiles, median, average, or other e.g. top 10%. These variables are typically related to farm structural characteristics, productivity or profitability (e.g. operating profit per mm rainfall or hectare, Browne et al. (2013); Planfarm and Bankwest (2013)). Variables can be combined, with for instance Kingwell et al. (2013) coding several financial indicators to define classes of performance, Stott et al. (2013) differentiating dairy farms according to intensification, or van Gool (2011) who divided land into potential productivity classes according to the incidence of several constraints. A spatial example includes the definition of agro-ecological zones by segmenting and crossing isotherms and isohyets (Planfarm & Bankwest, 2013).

Generating groups can also be done through “data-mining” [7/5]. This involves automated procedures able to integrate large amounts of data and numerous variables, when available. Methods include writing classifying protocols or using grouping statistics. For instance Kingwell et al. (2013) used a set of statistical techniques, including cluster and network analysis, in order to distinguish groups of farmers on the basis of social and managerial information. Zerger et al. (2011) employed spatial algorithms. Sherren et al. (2011) and Emtage and Herbohn (2012) both used cluster groups to develop typologies of farmers based on their socio-economic characteristics and attitudes toward natural resources management in order to explain their practices.

• “Content analysis” [24/33]. This methodological family grouped qualitative analysis procedures which involve the identification of dominant themes drawn from individual experiences, usually targeting specific groups of people. Often, identifying relationships between these themes and their elements is also an objective. Content analysis therefore stands in two overarching approaches simultaneously (Fig. 3.a). Although content analysis can be applied to any type of visual and textual material,
techniques in the sample nearly always focused on capturing the views, perceptions and preferences of farmers, recorded during interviews and illustrated by representative quotes. Content analysis is therefore largely dominated by social and psychological sciences. Rare counter-examples include Robertson et al. (2009) and Ransom and Trapnell (2011) who reported on technical aspects, for instance practical farm implementations issues. Otherwise, common topics include: how farmers’ personal experiences change, for instance regarding climate (Fleming & Vanclay, 2011; Head et al., 2011) or relationships (gender, Alston and Whittenbury (2012); institutional, Gill (2011)); which constraints are faced in specific sectors (meat marketing, Broderick et al. (2011); supply chains competitiveness, Nasiruddin et al. (2011); tomato industry transition, Pritchard et al. (2007)); which factors pre-empt the adoption of innovations, such as learning processes and sources of information (Ritman et al., 2011; Eastwood et al., 2012; McKenzie, 2013).

Three main method groups were identified, with the largest referred to as “coded themes” [14/13] (also termed “qualitative coding”). These procedures involve coding fully transcribed interviews in order to identify dominant themes. The coding analysis can be done manually (Moon, 2013; Raymond & Robinson, 2013) but is most often at least partially automated using the software NVivo®, hence representing a type of qualitative data-mining.

“Exploration” methods [6/6] could be considered a sub-group, since the principles involved are very similar. Open-ended questions are also preferred for flexibility, themes as well as the relationships they involve are identified and discussed. However, whilst the previous coding procedure remains relatively linear (i.e. questions elicit responses which are transcribed and then analyzed), exploratory protocols are much more iterative, involving a back-and-forth process between questions, responses and results which allows for a progressive construction of results, sometimes until explicit theoretical saturation (Gill, 2011; Cheshire et al., 2013; McKenzie, 2013). The explicit use of exploratory methods was found to be rare.

In contrast to these two method groups, “compilation” studies [7/7] use pre-defined questions and produce a commented summary of the group answers, often ranking them or presenting frequencies (McConnell, 2011). Of all the method groups identified, compilations provided the weakest quality of evidence, notably due to frequent sampling and procedural issues (e.g. questionable replicability, simplistic or absent methods, unacknowledged caveats and biases).
• “Participatory research” [16/12]. This methodological family grouped qualitative methods whose results were the product of a discussion. Common objectives are to determine what constitutes a representative farm (typically for use in system modelling), or which practices or views exist in a community. Three method groups were identified.

The most inclusive of stakeholders was named “collaborative” [6/3] and involves participants working together and discussing until reaching a concerted agreement. In order to define the characteristic of virtual farms, Armstrong et al. (2010) thus involved a varied industry steering committee, whilst Rodriguez et al. (2014) integrated both farmers’ and researchers’ perspectives into the research process.

Another method group was qualified as “elicitative” [7/6] and involved focus groups (often simply called workshops). During these meetings, the participants follow a discussion guide facilitated by a moderator who remains external (generally the researcher). Rather than a consensus, the moderator seeks to prompt and gather the existing diversity of views. Unlike content analysis, focus groups involve a specific pre-set procedure and tabulate the opinions of the group as a whole, not individuals. Examples include Cary and Roberts (2011) and Thorburn et al. (2007) who used focus groups to identify management practices, whilst Jackson (2010) gathered the views of farmers and consultants on grain productivity drivers.

A third group is referred to as “consultative” [7/4] and is characterized by successive steps, with the objective of refining results by consulting stakeholders in a pre-set iterative process. While their input can be considerable, the stakeholders’ involvement in the actual research process remains limited. Collaboration can nevertheless be part of the process, with for instance Zerger et al. (2011) who developed a draft map of revegetation priorities with regional personnel prior to seeking farmers’ views. Another consultative example is provided by Kalaugher et al. (2013) who gradually defined a typical farm by integrating the farmer’s and researchers’ separate perspectives into an elaborate framework that progressed through scoping exercise, pooling ideas, analysis, validation and evaluation. In its simplest form, consultative research consists of asking stakeholders to review results.

Categorizing the methods of this first overarching approach revealed that, saved for coding, the procedures used to capture and translate information were not always fully or well presented, in spite of their impact on downstream analysis. Specifically, two concerns were frequently identified: a lack of clarity regarding both terminologies and data origin.
These two issues were most evident in participatory research, mirroring the observations of Reed et al. (2009) about stakeholder analysis. Truncated theoretical framework, partial protocols and inconsistent nomenclatures, together with a profusion of techniques, maintained widespread confusion about meanings and doubts regarding transparency and replicability. Often a related issue, the criteria for participant selection were commonly over-simplified, when not overlooked. Many studies simply relied on local knowledge laced with value judgements, without consideration for representation bias or alignment with the study objectives (e.g. “progressive farmers were invited”). When participatory research was used for modelling, results were generally based on very small groups or case studies, complemented with sensitivity analyses. Either way, representativeness, relevance and objectivity concerns can legitimately be raised. This is particularly alarming considering the aims of participatory research.

A lack of explicit procedures was also found within the simple indicator groups - perhaps due to their apparent triviality. Even simple averages involve sampling choices, thus effectively starting the analysis and interpretation process. Yet the origin of summary statistics was commonly glossed over, even when studies procured second-hand data that was potentially produced for other purposes, and which characteristics may well impact the production and interpretation of results. Kingwell et al. (2013) provided a counter-example, describing possible representation caveats caused by data origin. Similarly, the sources for key attributes were not always justified, dated or even specified. The common recourse to assumptions, extrapolations and indirect information together with actual observations often blurred the distinction between real and built representations.

Likewise, the criteria upon which partitioning was performed were seldom justified, in spite of being the most common method to segregate a population. Pre-set arbitrary classes can impact results, for instance by hiding trends or by overlooking multi-modal distributions. Participatory and exploratory techniques can prevent these issues but are rarely used for segregation purposes.

Lastly, the overall issue regarding terminologies is perhaps best illustrated by the common terms of “survey”. This word effectively translated into a wide diversity of methods, depending on the target (everyone in a sub-group vs. varied sampling techniques), the study scale (national vs. local, large databases vs. small datasets), the type of information (nature, origin, collection procedure), how data is meant to be analyzed, and possibly transformed.
4.2 Identifying Relationships: Focus on Linking Elements

While the first approach largely exhibited an ancillary status, the opposite applied to the second overarching approach [59/54]. “Identifying relationships” almost always constituted the analytic core of studies. With a few exceptions, the methods groups described here can thus be considered as mainstream.

Qualitative approaches belonged to content analysis and most often involved coded themes (see previous section). Otherwise, determining how specific elements are linked meant identifying and quantifying which input(s) explain a given output. Objectives include isolating factors of importance (which ideally can be influenced to the desired ends), and providing grounds for predictions and extrapolations (to aid proactive decisions). A typical example is to assess the degree to which economic factors constrain the adoption of given technologies. The variables investigated ranged from farm physical characteristics and management practices to more intangible factors such as risk and resilience. A large number of studies aimed at explaining outputs related to productivity and profitability. Important variations included evaluating environmental externalities (e.g. emissions, contamination, erosion), which provide the study of farming performances with additional constraints. Another important research stream addressed farmers’ behaviors, most often in relation to the adoption of innovations or recommended practices, and mainly for production and for the sustainable management of natural resources. Explanatory variables likely to impact the farmers’ decision-making process commonly include demographic and socio-economic factors, as well as psychological traits such as individual perceptions, attitudes or motivations.

Similarly to the first overarching approach, numerous methods were found here. However, they proved easier to classify. This resulted in only three but large quantitative methodological families named “confirmatory statistics”, “mathematical programming” and “system modelling”.

- “Confirmatory statistics” [34/21]. This methodological family comprises tests and models which confirm the extent to which relationships between variables can be trusted to exist and to matter using statistical significance. Confirmatory statistics usually require a large amount of data but are powerful and flexible, which explain their great popularity: nearly all disciplines employ these research tools to successfully produce evidence despite the variability of observations, including when controlled experiments are not an option. Examples of topics explored were thus diverse, including: confirming the contribution of management to nutrient and water use efficiency at plot level (Anderson, 2010; Kirkegaard & Hunt, 2010); unravelling which
business indicators are associated with farming resilience at regional scales (Lawes & Kingwell, 2012; Kingwell et al., 2013); investigating the role of practical, social and psychological drivers in the adoption of innovations at farm or national level (Llewellyn & Pannell, 2009; Robertson et al., 2012a). Four method groups were distinguished.

“Statistical tests and correlations analysis” [19/6] are often simple procedures which essentially assess similarities between populations in terms of mean or distribution, and whether particular factors can be deemed to be associated with these differences (e.g. χ² tests, z-score, rank order correlations). For instance, Weller et al. (2013) detected that the capital structure of businesses chosen by farmers tended to be different across age groups but not across industries by studying proportional differences between population classes with.

“Statistical models” [26/15] often represent the more advanced stage of statistical procedures. Regression models are particularly ubiquitous and by far the most common. Robust and varied versions are available for both simple and multivariate analysis (Llewellyn & Pannell, 2009; Christie et al., 2011), with mixed models adding flexibility (Lawes & Kingwell, 2012). Non-continuous, categorical variables are also catered for with a variety of probit and logit regression models (D’Emden et al., 2008; Nossal & Lim, 2011). This large subgroup is often encountered in social studies where the answers of respondents are classified in a limited number of categories, with the binary extreme of yes/no. Convenient tools allow the most appropriate models to be selected, such as model ranking or the stepwise selection of factors.

The prior recourse to “data reduction methods” [7/3] which select variables is also an option. Examples include Factor Analysis (Rodriguez et al., 2014) and Principal Component Analysis (Greiner & Gregg, 2011).

A major drawback of statistical analysis is that proving relationships between variables does not imply causality. A rare, notable method endeavoring to address this issue is Structural Equation Modelling (SEM). Although technically a statistical regression model combined to factor reduction methods, SEM attempts to prove causality, or at least the existence of paths, by testing compound relationships that define “directional assumptions”. An example of such “causal modelling” [3/3] is provided by Price and Leviston (2014) who hypothesized and tested the ability of a specific set of sequential relationships between psychological, social and contextual variables to predict pro-environmental behavior.

• “Mathematical programming” [23/22]. Studies assigned to this methodological family are distinctive in that an analysis begins with an elaborate
mathematical construct. Concepts and problems are expressed as sets of equations using diverse types of assumed response functions. These include standard agronomical functions at field level (e.g. yield and economic response to nutrient application, Lawes and Robertson (2011)), production functions addressing input/output relationships at farm-level (e.g. structural adjustments and returns to scale, Sheng et al. (2011)), or utility functions which assume relationships between more subjective and intangible elements such as the perceived benefits or risks of, for instance, adopting a practice (D'Emden et al., 2006). These mathematical models, of varying complexity, are then tested ‘empirically’, i.e. using real data. Case studies, field observations, representative farms or modified databases are used to estimate the model parameters or to illustrate the model demonstrative abilities (Komarek & MacAulay, 2013).

Mathematical programming techniques most often belong to the fields of econometrics and production function theory, or more generally, production economics, measuring “efficiency and utility” [12/11]. As such, important topics include measuring agricultural efficiencies (productivity, profitability), and explaining choices made by farmers using rational economic arguments (Pannell, 2008). Methods include Data Envelopment Analysis (O'Donnell, 2010), stochastic distance functions (Cattle & White, 2007), duration analysis (D'Emden et al., 2008).

Another vast endeavor of mathematical programming is to support managerial decisions by providing optimal solutions to agricultural problems (Nuthall, 2011b). “Optimization” [13/13] procedures involve expressing conditions, then finding the parameters that typically provide the highest economic return. Diverse techniques exist, ranging from simply maximizing a response function (Lawes & Robertson, 2011) to using sophisticated solvers that combine equations and decision algorithms in order to accommodate numerous constraints (e.g. the international GAMS software, van Grieken et al. (2013)). An optimization technique that remains popular is linear programming, notably used in the prolific MIDAS model to allocate resources under competing circumstances for a specified production system of the Western Australian wheatbelt (Bell et al., 2008).

• “System modelling” [29/27]. Computerized representations of farming systems usually compile large amounts of information in order to evaluate current systems and assess alternatives. Constructing such models often represents a considerable synthesis exercise and collaborative effort. Investing in the development of these tools is justified by the further understanding provided by considering the whole rather than the parts alone (for instance leading to emergent properties, Asseng et al. (2010)), and
by their ability to fill gaps in data (for instance completing benchmark data, Kirkegaard and Hunt (2010)). A variety of tools exists that address questions at field, enterprise, farm or regional scales. Due to the complex and multi-disciplinary nature of farming systems, most studies use a combination of these tools in order to address several processes together. ‘Soft’ systems thinking that integrate qualitative elements is encountered (Kalaugher et al., 2013) but quantitative ‘hard’ systems methodologies largely dominate. Parameters are generally sourced from participatory methods, national surveys, one or several case studies farmers providing farm records, and/or expert knowledge. System modelling is a particularly vast and multiform domain whose numerous branches benefit from numerous specialized reviews (Le Gal et al., 2011; Martin et al., 2012; Robertson et al., 2012b, etc.). For the purpose of this synthesis, three method groups were distinguished.

“Simulators” [13/12] are defined here as detailed biophysical tools used to predict agricultural outputs under various climate and management scenarios, generally calibrated with historical climate data and field experiments. The most prevalent crop simulation model in Australia is APSIM. Originally developed locally for farming systems as varied as temperate cereals or tropical sugarcane (Webster et al., 2009; Kirkegaard & Hunt, 2010; Thorburn et al., 2010; Biggs et al., 2013), its numerous modules are used and continuously improved by a large community of scientists globally. Typical examples include investigating the potential consequences on productivity and on the environment (e.g. gas emissions, nutrient losses) of adapting to climate change by changing management practices. Browne et al. (2013) and van Gool (2011) provide other examples of simulators.

“Organizers” [12/12] comprise models which focus on the organization of farming systems. Applications include identifying the benefits of various management strategies or explaining current adoption levels by investigating resource allocations, option combinations, constraint variations. Usually these models use average years and at least some economic perspective. For instance using the whole-farm model MIDAS and its “Land Management Units”, Kingwell (2011) explored the performance and economic implications of increasing farm complexity, whilst Robertson et al. (2010) investigated the benefits of adopting various amounts of break crops. Other modelling examples exist for crop sequences (Lawes & Renton, 2010), field operations (Webster et al., 2009), management strategies (Rodriguez et al., 2014). Most focus on matters internal to the farm, although modelling the organization of farms in a given agricultural space is encountered (Asseng et al., 2010).

A third method group comprises tools of varying complexity that focus on a very specific aspect and can be referred to as “calculators” [21/18]. Standard, custom-
built or derived from other models outputs, calculators can be used alone, as building blocks for simulators and organizers, or as linkages between complementary aspects. For instance, agronomic input or output calculators improve or expand simulators (Christie et al., 2011; Lawes & Robertson, 2011); accounting and financial tools add economic indicators (Bell et al., 2008; van Grieken et al., 2010); whilst stochastic and sensitivity analysis complete results with risk assessments by modelling a likely range of variations (Monjardino et al., 2010; Heard & Leddin, 2012).

The connections existing between the three methodological families identified above should be highlighted. Notable examples include organizers based on optimization techniques, or using statistical tools to test the significance of estimated parameters in mathematical programming, or to assess the explanatory power of theoretical and simulated relationships. Complexity also blurs methodological frontiers, for instance when mathematical models reach scopes that are characteristic of system modelling.

Although intertwined, the methods of this second overarching approach proved much better established than the first approach, with generally clear protocols and consistent terminologies. In other words, the studies demonstrated greater care to analytic technicalities than to the origin of the data worked upon. For instance, retracing model mechanisms was often easier than sourcing its base parameters. Likewise, statistical and mathematical models were usually entirely explicit, however the nature, quality, and relevance of the sample used were often very briefly described or not referenced at all. Correspondingly, the success and mainstream status attained by some computer programs, typically in system modelling, raises the concern that methods (and research objectives) become tailored to the tool (and its constraints), rather than the reverse.

A second general observation is that the rarer qualitative methods were mostly represented by one method group, namely coded themes within content analysis. They also covered a more restricted range of themes, with social topics much better covered than technical ones. Quantitative studies proved more eclectic in spite of facing practical issues when addressing social matters, large datasets being required to compensate for the necessary simplification imposed by coding techniques. Nevertheless, system modelling and exploratory techniques showed particular promise to integrate both qualitative and quantitative information. Yet, disciplinary boundaries endure: system modelling has become a polymorph field of mainstream status but remains dominated by quantitative thinking tailored to agronomy and economics,
while exploratory techniques are only marginally used and focus on qualitative information for social sciences.

4.3 Retracing Processes: Focus on Establishing Causality
The third overarching approach [45/39] places current observations within a succession of events, investigating how social, economic and technical mechanisms shape agriculture. This overarching approach was the least common. Relatively few studies aimed at producing new knowledge by explicitly investigating long-term evidence. Many did consider the past but with the aim of compiling existing knowledge, positioning their particular objectives or theoretical framework within the wider scope of their topic, or providing background information against which interpreting, comparing and extrapolating results (including calibrating simulation tools, typically using historical climate data and farm records). Overall, agronomy was much less represented than economics and social sciences, with rural studies often making social issues and industry dynamics their specific objects of study.

Three contrasted methodological groups were identified. The largest encompasses “time series”, a quantitative tool used by a variety of disciplines. The main alternative was “narratives”, i.e. exploring farmers’ experiences qualitatively. Lastly, an anecdotal number of publications aimed at “reconstituting” past situations.

- **“Time series” [32/22].** The most common manner of addressing the past is quantitatively, through the use of time series which essentially come from collecting descriptive statistics throughout time. The resulting large amount of data allows investigators to follow changes in a population for demographic, physical and economic variables. Such data is either collected by national monitoring programs, or sold by consultancy firms. Collecting quantitatively any other types of information pertaining to farmers’ history is notoriously difficult. Studies endeavoring to do so usually require the input of several hundred interviews coded toward the analysis of very specific topics. Examples include Wheeler et al. (2012) who collected long-term data on farm succession issues in irrigated agriculture. In adoption studies, Llewellyn et al. (2012) and D’Emden et al. (2006) circumvented the data scarcity issue by gathering time-dependent variables.

  Time series can be analyzed by studying their “patterns” [25/11]. Kingwell and Pannell (2005) thus extrapolated on the future of broadacre farming by comparing several long-term economic trends and inferring on the scope of their variations; Llewellyn et al. (2012) evaluated the diffusion of no-till technology by interpreting cumulative adoption frequencies as a classic adoption curve; Tonts et al. (2010) used
records since 1800 to distinguish distinct phases in the introduction of cattle breeds in Australia.

Alternatively, time series can be analyzed using confirmatory statistics or mathematical modelling methods [17/15], typically producing productivity analyses by aggregating data at state or country scale (Sheng et al., 2011). Otherwise, single farms act as study cases (Komarek & MacAulay, 2013). Large and complete datasets allowing time-dependent analysis at the scale of individuals are seldom available. Lawes and Kingwell (2012) and Kingwell et al. (2013) provide such rare examples, in which hundreds of broadacre farmers provided decade-long economic and production indicators that permitted the longitudinal analysis of business performances.

• “Narratives” [20/17]. In this qualitative methodological family, the past is explored though the lens of personal experiences, to determine how current situations came to be.

“Individuals” based studies (or “case studies”) [7/7] are characterized by investigating few people at length (rarely more than five) with the objective of reconstructing personal circumstances and the resulting paths with in-depth details. The evidence collected is in essence qualitative (e.g. storylines or biographies providing explaining past decisions), but can include quantified specifics as well (e.g. budgets and rainfall records). The quality of evidence provided by case studies ranges from questionably weak, as warned by Tonts et al. (2012), to strongly defended. Eastwood et al. (2012) and Gill (2011) thus followed very explicit procedures supported by elaborate theoretical frameworks that emphasized the wider relevance of their results.

Other studies aim at identifying “groups” commonalities [13/10]. Whilst conclusions also rely heavily on individual examples for illustrations, results are built from a pool of evidence coming from several people, not dissected from particular stories. To build parallels with quantitative research, these studies analyze data in an aggregated form, as opposed to case studies which researchers often refer to as “providers of longitudinal information”.

Almost all examples in this methodological family employed methods and covered topics pertaining to content analysis on the topics of change and transition.

• “Reconstitutions” [5/5]. Lastly, a marginal methodological family was identified. Instead of focusing on individuals or given groups, these studies broadly contextualized their object of study, be it case study farms (Beilin et al., 2011), a technology (Wilkinson, 2011), a value chain (Oro & Pritchard, 2010), a region (Allison & Hobbs, 2004), or an industry (Tonts et al., 2010). Contextualizing is done by
triangulating information together with considering wider temporal and spatial scales, typically including a variety of sources. Results include distinguishing historical phases, retracing processes, and contrasting timelines. Conceptual frameworks are used that recognize the need for the systemic characterization of complex situations in order to assess change and transition. These characterizations lead to the identification and comparison of development pathways, with generally much greater scopes than case studies. In spite of the few examples encountered, two methodological families were tentatively distinguished.

First were “retrospective” studies [3/3] which revisited existing information. These differed from standard reviews or historical narratives in that new knowledge was produced, typically using the analytical lens of a novel conceptual framework. For instance, Allison and Hobbs (2004) applied the concept of social-ecological systems to the Western Australian wheatbelt to reinterpret historical cycles.

Second were “investigative” studies [2/2] which added an important field component to their analysis, integrating novel material to existing documentation. This is the case with Oro and Pritchard (2010), who based their comparative analysis of value chains trajectories on varied documents and on interviews.

A major characteristic of this third overarching approach was the use of tools belonging to the first and the second approach. This was in spite of the difficulties of sourcing sufficient (quantitative) and representative (qualitative) information, and in spite of the existence of specifically suited concepts and methods e.g. social-ecological systems, evolutionary economic geography and life cycle theories that were very little employed, or agrarian system concepts that were not encountered altogether. These frameworks are not new (Boschma & Martin, 2010; Cochet, 2012; Darnhofer et al., 2012; Gautier & Kull, 2015), raising the question why methods that should have passed the stage of emerging tools remain greatly under-used. These observations corroborate Tonts et al. (2012)’s critical appraisal of Australian academic traditions in rural sciences.

Concurrently, and as a conclusive note to the description of the method map (Fig. 3), it should be pointed out that publications employing mixed methods were rare as well: only 13% employed both qualitative and quantitative methods (Fig. 2). Regrettably this is a poor improvement on the low numbers identified by Bryman (2006) a decade ago for Australian mixed methods in social fields.

Further work could assess why methodologies that make use of qualitative and historical approaches are under-used. Possible reasons may include a lack of: compatibility between conceptual frameworks; awareness among agricultural scientists
(e.g. disciplinary and topical divides notably technical/social); expertise in qualitative and mixed methodologies (e.g. due to lack of relevant education programs); communication and collaboration across disciplines (e.g. rare transdisciplinary programs); funding to support novel or under-used research procedures (e.g. innovative projects perceived as “risky”).

5. Notes on the Interpretative Procedure and its Outputs

The interpretative review procedure that was chosen proved successful in achieving the ambitious goal of this study. Detailed methodological aspects (principles) as well as method use (relative frequencies) were addressed across a particularly broad range of topics and disciplines that are all relevant to the study of agricultural systems. No similar example could be found in reviews using systematic procedures. The novelty of interpretative approaches for agricultural research justifies highlighting key strengths and limitations identified during the review process.

5.1 Strengths

The flexibility permitted by the progressive development of classification criteria was an undeniable asset, allowing definitions to be validated, rejected or adjusted with new information. Sorting methods according to pre-defined criteria such as disciplines, topics or data type was trialed but could not encompass all the publications of the sample, especially those featuring rare methods. In fact, it appeared early that unlike focused methodological classifications (e.g. Renting et al., 2009; Le Gal et al., 2011; Kraaijvanger et al., 2014), categories in this study could not be structured according to the same analytical dimensions.

The possibility to access detailed publication content also proved crucial to determine precise classification criteria, as well as to sort out methodological subtleties that were frequently complicated by inconsistent terminologies. This common problem is noted by reviewers even within given fields or topics (e.g. Brym & Reeve, 2016). Here, terminology issues were particularly evident for qualitative research. This may be a symptom of the general fragmentation of scholarly communication that was identified by Varga (2011) within sociology. Worse, distinctions between qualitative and quantitative methods were sometimes unclear in spite of their fundamentally different principles (e.g. within compilations and participatory research). Manual sorting was already difficult, so automated indexation via algorithms had little chance to succeed. Many of these studies could have been discarded using quality criteria (Heyvaert et al.,
However, and although this review highlighted concerns regarding result validity, the primary goal was to assess method use. Reports and other industry publications that may have had less stringent peer-review processes were included considering their impact within the non-academic community.

A third key strength was the ability to include both quantitative and qualitative studies. Continuing review efforts that assess all types of analysis methods is essential given that qualitative research is still under-used, often misused or considered as a mere companion tool, its contributions mis-understood and thus undervalued (Dixon-Woods et al., 2006a; Northcote & Alonso, 2010; Nuthall, 2011a). This was confirmed here, with Australian research remaining highly quantitatively oriented. It is, however, not a new problem in agriculture, in which the enduring lack of qualitative methods, and consequently mixed methods, has led authors to ask at least since the 90s whether protocols are chosen depending on the research problem, or whether the problem is chosen depending on which available techniques predominate (Bitsch, 2005).

5.2 Limitations

The main weakness of the review procedure applied here regarded the initial search strategy. Cross-disciplinary reviews are generally large projects, involving multi-disciplinary teams that are able to draw from several databases and to undertake workshops to further benefit from the input of experts (Dixon-Woods et al., 2006b; Pearson et al., 2011; Heyvaert et al., 2013). These options were not available for this study (one investigator). Whilst the data thus benefited from more standardized treatment, searches and analysis were slower, resulting in an initial pool of retrieved items that possibly over or under represented some fields. For instance, a lack of geography studies was noticed that may be related to the choice of keywords. This could also simply be linked to the sizes of research communities, their orientation and their publishing preferences, which all influence the number of publications available as well as citation metrics (Barbier et al., 2012). However, it was not the aim of the review to produce a representative sample of agricultural topics, but to cast a net wide enough to cross disciplinary boundaries.

Another concern regarded a number of studies that repeatedly appeared at the top of search results. This highlighted the overwhelming influence of citation numbers and author prominence as criteria for ranking “relevance” in Google Scholar. These metrics effectively favor mainstream methods in a snowball effect while eclipsing marginal methods, irrespective of their quality and originality. The issue was answered with non-random additions which, in spite of remaining few, proved indispensable to
complete the method map. In future studies, a comparison of search results with other academic engines would be valuable.

Lastly, the emphasis of this review on protocols and terminologies may be critiqued. There is no doubt that nomenclature consistency matters less than methods being adequately used. Beyond the efforts of this broad-scope synthesis, specialized reviews are necessary to fully evaluate whether this is the case. Nonetheless, the above results can be used to argue that higher nomenclature standards may be a necessary step to increased methodological quality, recognition and use.

6. Conclusion

A broad-scope yet detailed multi-disciplinary review was undertaken of the varied methods used to analyze agricultural systems. No similar review could be found in the agricultural literature. The practical challenges of synthetizing a large and diverse body of literature could not be done using bibliometric information and automation, which made a standard systematic review not possible. The interpretative procedure chosen instead, novel in agricultural research, produced an overarching framework categorizing the diversity of approaches and methodologies encountered. This new information was summarised in a “method map” format.

The results, notably the criteria retained to classify methods, can be used to critically assess the research practices of agricultural research communities. Here, with the case of Australia and New Zealand, methodological weaknesses were identified. These led to highlight the need for more careful accounts of how data is sourced, and for more consistent terminologies, particularly regarding qualitative methods. The relative use of methods and their relationships in terms of underlying principles and common combinations was also assessed. This determined mainstream and marginal methods, notably here regarding the use of some qualitative and long-term frameworks. Further research could determine why this situation endures. Applications include helping orientate research efforts, stimulate discussions about research design, or make practical suggestions to increase transdisciplinarity. For instance, the use of mixed methods could be increased through teaching and active promotion among agricultural scientists. Other interesting lines of further examination include comparing Australian research strategies with the practices of other communities. Each section of the method map could also be enriched using specialized reviews. Changes in dominant methodological paradigms could be monitored, discrepancies between what is recommended and what is used determined in greater detail, and the value to the current situation of new, emerging and marginal methods further investigated.
Acknowledgements

This work was funded by the Australian Government, Department of Education (IPRS/APA scholarship), and by the Grains Research and Development Corporation of Australia (GRDC, GRS scholarship). The authors also thank Stephen Powles for his continued support, as well as Zoe Leviston, Lindsay Bell and three anonymous reviewers for valuable comments on the manuscript.

References


2.3 Conclusions:

Comparative agriculture is relevant

This study produced a broad-scope yet detailed review of the methods currently used in Australian farming system research. To do this, a novel review procedure was used which allowed to: (i) include quantitative, qualitative and mixed methods studies; (ii) cover a particularly wide range of topics and disciplines from agronomy to environmental and social sciences; and (iii) investigate levels of detail not permitted by the mainstream methods usually employed to produce systemic literature reviews. The study and its outputs thus hold relevance beyond Australia.

The broad-scope methodological picture produced largely confirmed the hypothesis of this chapter: first, no comparative agriculture studies were encountered, and second, no equivalent approach was encountered. The relevance of comparative agriculture was demonstrated with:

- Rare related frameworks: social-ecological systems, political ecology and evolutionary economic geography were very seldom encountered;
- Rare methodological similarities: techniques resembling some used in comparative agriculture do exist, notably exploration and investigative reconstitutions, however these were found to be very marginally used (Fig. 1.a);
- Few mixed methods: the methodological qualitative/quantitative divide endures (Fig. 1.b);
- Few holistic studies: similarly, the topical social/technical divide largely continues (with the main exceptions represented by modelling studies); and,
- Few farming diversity studies: this area of study is only little addressed, and mostly using quantitative methods (arbitrary segregation with classes, and data mining with multivariate clustering, Fig. 1.c).

The conclusion of this chapter is that methodological and conceptual gaps do exist in Australian farming system research and comparative agriculture could make a useful contribution (Fig. 2). To test this, applied work was conducted in the Western Australian wheatbelt and is described in the next chapters (Fig. 3 & 4).
Fig. 1. Methods used to study agricultural systems in Australia: prominence and linkages.

The new methodological classification produced in this study and represented here with a network graph comprised 11 methodological families (blue nodes: quantitative, yellow: qualitative) spread over 3 overarching approaches (green backgrounds). Although methodological similarities were found (a), they were rare and no procedures equivalent to those of comparative agriculture were encountered. Mixed methods were relatively rare (13% of the 92 publications included). Comparative agriculture could contribute bridging the divide between quantitative and qualitative approaches (b), as well as the overlapping topical divide between technical and social aspects that are generally studied separately. Lastly, comparative agriculture is particularly relevant given the lack of studies that specifically investigate farming diversity (c).

Fig. 2. Thesis structure. Chapter 2 completed.
Fig. 3. Thesis structure. Next sections: Chapter 3 & 4.

Fig. 4. Study area outlook. Typical features of the central region of the Western Australian wheatbelt where the methods of comparative agriculture where applied: broadacre landscape dominated by cropping and typical farming equipment.
CHAPTER 3

Methodological capabilities of comparative agriculture:

Assessing regional farming system diversity in a broadacre region (article, text)

This section reproduces verbatim the revised version of the article submitted for publication to Geoforum on the 20th of May 2017 (first submitted 5th of January 2017).

1. Abstract & Introduction: Practical challenges of holistic assessments 76
2. Material & methods: The agrarian system & the agrarian diagnosis 79
3. Results: Farming system typology vs. statistical farm clusters 92
4. Discussion: Analytical choices, methodological tools, conceptual originality 105
5. Conclusions, Acknowledgments, References 114
Assessing regional farming system diversity using a mixed methods typology: the value of comparative agriculture tested in broadacre Australia

Myrtille Lacoste*, Roger Lawes2, Olivier Ducourtieux3, Ken Flower1,4

1 The University of Western Australia, School of Agriculture & Environment, Crawley, WA 6009, Australia
2 CSIRO Ecosystems Environment, Floreat, WA 6014, Australia
3 AgroParisTech, University Paris-Saclay, UFR Comparative Agriculture, UMR PRODIG, 75005 Paris, France
4 The University of Western Australia, Institute of Agriculture, Crawley, WA 6009, Australia

* Corresponding author at: The University of Western Australia, School of Agriculture & Environment M086, 35 Stirling Hwy, Crawley, WA 6009, Australia
E-mail address: myrtille.lacoste.uwa@gmail.com (M.Lacoste)

Highlights

- A 6-step procedure to assess agricultural diversity in terms of farming systems is presented
- Mixed methods solved applied challenges: holism, data scarcity, representativeness, cost-efficiency
- Empirical analysis and original concepts contributed to successfully define farming systems
- Corresponding farm groups differed across 36 biophysical, managerial and social variables
- Farm clusters produced with multivariate clustering were contrasted across fewer variables
Abstract

Farm and farmer typologies typically focus on specific aspects and are usually based on standard structural and socio-economic indicators. Regional assessments of agricultural diversity based on farming systems are more rarely done, as farm and practice information that is representative and detailed enough is difficult to collect. The discipline of comparative agriculture specifically addresses these challenges but remains little known, and seldom applied to broadacre situations. This study demonstrates in Western Australia the value of its mixed methods and multidisciplinary concepts to determine the level and nature of regional farming system heterogeneity.

The typology built comprised six farming systems based on 36 farms that represented half the farming population of a 4 000 km$^2$ area (broadacre rainfed systems dominated by winter cereals and sheep, Mediterranean climate). The farm groups corresponding to these farming systems differed across 36 variables. Biophysical, technical, and social aspects at varied spatial and temporal scales were covered. Simple classifications rules were deduced from the typology for extrapolation and further application.

Results were compared with five sets of farm clusters produced through multivariate clustering procedures commonly employed to build typologies. These farm clusters differed across fewer variables than the farm groups of the comparative agriculture typology. The analytical, methodological and conceptual tools used in comparative agriculture to solve the challenges associated with the holistic study of farming system heterogeneity are discussed. These included basing data collection and analysis on an empirical approach that assessed groups of farms rather than individuals, solving data scarcity through a range of qualitative techniques, and progressively informing the choice of typology criteria. Comparative agriculture thus provides an alternative to standard typology paradigms that deserves wider application.

**Key words:** Farming systems; Agrarian systems; Farm typology; Farmer practices; Mixed methods; Multivariate cluster analysis
1. Introduction

Farming systems research explores complex mechanisms, such as how farm enterprise mix and productivity interact with agronomic processes, labour requirements, commodity markets, climate, machinery and scheduling operations. Such explorations often require detailed information about the current status of the farm and the organisation of its resources. Regional assessments of the diversity of farming systems are also needed to determine how variable the processes investigated are. This information is necessary to identify which mechanisms should be addressed, the extent to which they can be impacted, and to whom in the farming population and where in the landscape such decisions may apply. Some form of classification that aggregates farms into relatively homogenous groups is required to capture the heterogeneity of farming systems. These groups can be used to define types of farming systems, which together form a typology, i.e. a tool that provides researchers and decision-makers with a simplified yet relevant representation of the diversity of situations encountered within the region (van der Ploeg et al., 2009; Tittonell et al., 2010).

Numerous typologies have been constructed for a variety of purposes (see for instance references within Emtage and Herbohn (2012) and Kuivanen et al. (2016b)). However, most typologies are based on a given range of farm or farmer characteristics and do not necessarily match farming systems, i.e. the structural and functional organisation of the farm that underpins its production processes (Vanclay et al., 2006; Sturaro et al., 2009; van der Ploeg et al., 2009). Efforts are generally made to consider several farming aspects; however, holistic procedures that take into account complex relationships between multiple indicators across the entire farm are rare. For instance, Valbuena et al. (2008) and Blazy et al. (2009) noted that landscape attributes are rarely integrated. In addition, the few examples of farming system typologies available are limited to regions where agriculture is quite diversified (Tittonell et al., 2005; Choisis et al., 2012; Kuivanen et al., 2016b). Examples are particularly lacking in broadacre agriculture. Instead, farm typologies in these regions focus on particular aspects such as sub-systems, financial performances, given practices, farmers’ attitudes or perceptions (Greiner et al., 2009; Waters, 2009; Sherren et al., 2011; Emtage & Herbohn, 2012; Kingwell et al., 2013; Stott et al., 2013; Aouadi et al., 2015). Alternatively, farming populations are separated into groups based on factors such as farm size and financial attributes (van der Ploeg et al., 2009; ABARES, 2016).

The difficulty of addressing regional heterogeneity in terms of farming systems resides in deciding which variables are most relevant, and which process to follow to aggregate farms. To be valid, a typology of farming systems must be based on groups of
farms that are different in terms of farming resources and productions, which include their nature, amount, organisation, and conditions of renewal. Land, labour, financial and human capital, as well as the local social relationships of production and trade, are combined into specific management strategies and productions. Each component is nuanced, with interactions spanning several temporal and spatial scales (seasonal, yearly or longer time frames at the plot, farm or regional levels). To reflect the farming system mechanisms, a range of both structural (e.g. hectares, equipment, labour units) and functional (e.g. scheduled operations, resources allocation, nutrient fluxes) variables must therefore be included when aggregating farms. Social variables may also be relevant, for instance when aspects of the family unit or farm history influence the organisation of labour, or when societal and institutional circumstances impact the access to goods and services.

As a consequence, a farming system typology implies that many agronomic, economic, environmental and social variables, all potentially of importance, must be considered. However, farm information that is representative and detailed enough to appraise the heterogeneity of farming systems is rarely available and is difficult to obtain, even in industrialised countries where agricultural census are regularly conducted (Aouadi et al., 2015). Big data and remote sensing can generate large amounts of bio-physical information, but details about agricultural resources and practices remain scarce as collecting farm, farmer and rural information rapidly becomes costly, highly demanding in resources, and difficult to manage (Navarro et al., 2016). The issue is further made more complex by the inherent variability of agriculture that generally requires large datasets for significant relationships to be identified, and by the need to include long-term information to avoid capturing static pictures of systems that are constantly changing (Iraizoz et al., 2007).

This study used the multi-disciplinary concepts and applied mixed methods of comparative agriculture (Cochet, 2015) to solve these issues and determine the typology criteria that could adequately capture regional variations in terms of farming systems. This integrative discipline remains little known in English-speaking academia (Hervieu, 2012; Gautier & Kull, 2015; Lacoste et al., 2017). Published examples applied to broadacre situations are particularly lacking.

The holistic framework of comparative agriculture emphasises the need for in-depth investigations that are grounded in field work and integrate both technical and social aspects at varied spatial and temporal scales (Mazoyer & Roudart, 2007; Cochet, 2012; Moreau et al., 2012; Aubron et al., 2016). The validity of such a typology was examined for its ability to capture and describe the heterogeneity of farming systems in a broadacre region of Western Australia. First, the effectiveness of the methods used
was tested by assessing whether the groups of farms discriminated by the typology differed in terms of farming systems, i.e. across a wide range of structural and functional characteristics at both field and whole-farm scales. Second, the extrapolation potential of the typology was tested by using its results to define simple classification rules. These rules were applied to the original dataset, and the resulting farm groups compared with those of the typology. Third, the performance of the methods used was compared with that of multivariate procedures commonly employed to define farm and farmer typologies. This was done by comparing the number of variables that differed between the farm groups of the typology and between farm clusters produced statistically, i.e. by showing the extent to which each classifying procedure provided insights regarding the diversity of the farming population studied (maximum homogeneity within groups and maximum heterogeneity between groups, Iraizoz et al. (2007); Emtage and Herbohn (2012)).

These results are then discussed, showing how the methods of comparative agriculture solved issues related to the characterisation of farming diversity, and how its typologies differ from those dominating the literature on farming diversity.

2. Material and methods

2.1 Region and study area

The study area occupied approximately 4,000 km² and was located in the Western Australian wheatbelt, one of Australia’s main grain growing regions where the main productions are cereals and sheep (117°28’E, 31°23’S, Fig. 1a). Across this 20 million hectare region, about 4,000 rainfed broadacre farms, most of which are several thousand hectares in size, produce ten million tons of grains. This includes a third of the country’s wheat tonnage, produced with yields slightly less than 2 t/ha on average (ABARES, 2014). The location was chosen for its central position in the wheatbelt, where ongoing applied and modelled research would allow for comparisons and further use of results.

The climate is Mediterranean-type, with hot dry summers and mild wet winters. Annual rainfall is low and variable, on average 300 mm, about 65% of which occurs during the growing season between May and October (BOM, 2015). There is one winter crop per year, followed by a summer fallow. Crops are seeded in April-June and harvested in November and December. The majority of farm businesses are crop dominant in no-tillage systems (knife-points seeding). The main crops are wheat, barley, canola, lupin. Sheep mostly graze annual volunteer pastures and crop stubbles, sometimes legumes pastures. Although the region is dominated by sands and low relief, soil heterogeneity is high. Further information about the study area is available in Lacoste et al. (2016).
Fig. 1. Region and study area: location and spatial heterogeneity.
Landscape zones provide a simplified agro-ecological representation of the region’s high soil heterogeneity. They integrate topography, dominant textures and land use. Most farms in the region are several thousands hectares in size and often cover several landscape zones. Sources: Galloway (2004); DAFWA (2014); Lacoste et al. (2016).

2.2 Farming system typology: procedure, sample, data

Procedure. To produce a typology capturing the diversity of farming systems existing in the study area, an agrarian diagnosis was conducted over 12 weeks by one investigator during May-August 2014. Also called agrarian system diagnosis-analysis and usually conducted at relatively small regional scales, this mixed methods procedure applies the multi-disciplinary concepts of comparative agriculture (Barral et al., 2012; Cochet, 2015). It consists of an iterative process during which direct observations and farmer interviews are central, data collection and analysis are largely conducted concurrently, and the information to be collected is progressively prioritised. This allows reducing the complexity of the agricultural situation using informed decisions while keeping the investigation manageable, collecting both qualitative and quantitative information that is representative and high quality. The steps of the agrarian diagnosis are summarised in Fig. 2. In this study they were conducted as follows:
Steps 1 and 2: Landscape and history (data collection: 3 weeks of observations, then 4 weeks for 17 interviews involving 22 respondents). An agrarian diagnosis starts with investigating spatial and historical factors explaining variations in management in the area. For instance, retired farmers were asked to explain when, where, and how their productions and practices changed. Largely explorative, these first two phases are crucial for preparing the detailed investigation of current systems and were described in detail in Lacoste et al. (2016). Results included the identification of relatively homogenous agro-ecosystems at different scales, namely three landscape zones composed in varying proportions of three major soil types (Fig. 1.b), as well as guidelines for farmer interviews.

Steps 3 and 4: From farmer interviews to farming system typology (data collection: 5 weeks, 38 interviews involving 48 respondents). Detailed farm and practice information was then collected from a purposive sample of managers using semi-structured interviews (see next paragraphs). As interviews progressed, farming businesses were segregated into relatively homogenous groups according to similarities in overall structure and functioning. These groups of farms provided the basis on which the farming systems were identified and the typology was built, using typical situations bounded by ranges of existence (Fig. 3). In this study, the farming systems modelled were production systems (whole-farm level) composed of cultural systems (crops and pastures) and animal systems (sheep) (see Fig. 4 for definitions). Interviews were conducted until a situation of theoretical saturation occurred, i.e. (i) no new important information was uncovered, (ii) the typology remained stable, and (iii) sufficient information was collected from individual farm businesses to describe the key activities and strategies of each farming system. To confirm results statistically, additional interviews were conducted.

Steps 5: Farming system performances. After characterising farming system types, their technical and economic performances are calculated and compared (not presented here).

Steps 6: Feedback on preliminary results. A draft of the typology and associated results were presented locally during two presentations in October 2014 to ensure the adequacy of the first conclusions, and completes the ethical requirement of providing direct feedback to respondents. This participatory cross-validation did not result in any major modifications.

Further steps: extrapolations. Uses of a diagnostic include extrapolation to the entire farming population of the studied area. In this study, classification rules that could be used for this purpose were defined (see section 2.4). Extrapolation to larger regions may also be possible. As shown in Fig. 1.a, results could be potentially relevant to the entire Mortlock sub-region, across which similarities in biophysical characteristics and land use were noted by Galloway (2004).
Fig. 2. Agrarian diagnosis: applying the concepts of comparative agriculture.

Comparative agriculture is a discipline that is defined by Cochet (2015, p.7) as “the science of transformations and adaptations of agricultural development processes”. An agrarian diagnosis is a procedure that applies the multi-disciplinary concepts of comparative agriculture to determine the mechanisms underpinning agricultural production and changes, with a focus on applicability to research, development and extension. To do this, major outputs include the identification and comparison of: agro-ecological zones (1); farming trajectories (2); typology of current farming systems (3-4); and the technical and economic performances of these farming systems (5, not presented here). This is achieved through a set of mixed methods during which qualitative (Ql.) and quantitative (Qt.) types of data collection, analysis and results are iteratively combined to determine which farming systems exist in the study area. These farming systems are partially identified during step 2-3, then refined and characterised during a modelling process (4, detailed in Fig. 3) that uses a conceptualisation specific to comparative agriculture (Fig. 4). Foundation principles include considering systems (i.e. organised sets of components and their interactions), achieving holism (i.e. including all relevant aspects), and using representative quality data, while keeping the investigation manageable and cost effective (progressive prioritisation, flexibility, bias avoidance, etc.). The procedure is not participatory except for the presentation of results to local stakeholders for feedback, validation and communication requirements (6). Statistical analysis in not necessary to build the typology but can be conducted to contribute to its validation, as done here (4). (Fig. 3) (Fig. 4).
Fig. 3. Defining a farming system typology using an agrarian diagnosis: from individual farming situations to modelled farming systems.

In comparative agriculture, *modelling* consists in performing an informed reduction of the observed variation is undertaken to facilitate comparisons and the assessment of complex situations. During an agrarian diagnosis, the iterative nature of the modelling process involves repeatedly analysing the dataset to first hypothesise the existence of patterns, then progressively confirming and hierarchizing them to refine the approximation of final values and boundaries based on information gathered throughout the investigation. This is completed when theoretical saturation occurs, i.e. when improvements become marginal. Importantly, the typical values defining farming systems must represent the “heart” of each system, i.e. its specificities in terms of structure and functioning. Therefore, those typical values do not necessarily correspond to averages or medians. Modelling decisions are primarily based on the quantitative data collected, but also integrate qualitative information and triangulation with published material when available. Only two discriminating criteria are represented here (axis), however their number, nature and importance vary and are identified during the investigation. When describing farming systems, comparative agriculture emphasises the importance of a wide, holistic perspective. Many defining variables may thus be retained as informed simplifications do not equate simplistic aggregations.
The term *farming system* is used in this study in a broad, general sense to qualify agricultural representations that integrate whole-farm considerations. In contrast, the terms presented in this figure i.e. *cultural system*, *production system* etc., refer to comparative agriculture concepts that represent specific farm components and distinct scales. Each is a modelled, realistic simplification summarising the situation of a group of farms sharing relatively similar conditions and practices, and each linked through specific relationships of complementarity and competition. In this study, the *activity systems* level was not modelled, as non-agricultural activities supplementing the household income did not normally impact farming processes in the area. Beyond the farm level is the regional *agrarian system*, defined by the set of systems identified at small regional scales (one or several typologies) together with the social, economic and environmental factors allowing their reproduction and impacting their evolution (including institutional and political). At larger scales, neighbouring agrarian systems compose the agricultural situation of a large region or nation (Mazoyer & Roudart, 2007). In this study, the boundaries of the agrarian system are likely to exceed those of the Mortlock sub-region (Fig. 1.a).
Sample. To ensure adequate representation, a purposive sampling technique was used by which the current managers of farming businesses were first selected at random then stratified per landscape zone and farming system (progressively defined, see Fig.2). The identification of participants was achieved by mapping, scouting and snow-balling (no reliance on existing farm listings). Recruitment was made in-person door-to-door (cold-calling), by presenting the aim of the study and emphasising voluntary participation, confidentiality and anonymity, the possibility to re-schedule and to opt out. No payment or compensation was offered, only the potential value of the study for the respondent and the region (external perspective to identify farming profiles), and the assurance of providing respondents with the results of the study (the 2 local presentations, as well as a summary sent by email). Farming systems were identified after a dozen interviews with farm managers, but additional respondents were sought to ensure the thorough characterisation of each system and answer the statistical requirements of this study. Interviews were always conducted face-to-face, and mostly one-on-one with some contributions from spouses. In total, 38 interviews involving 42 respondents were conducted (response rate: 97%), discarding only one which was incomplete. The resulting sample contained 36 farming businesses which, based on information collected during the investigation, represented about half the farms of the study area.

Interview structure and collected data. Interviews were in-depth and semi-structured, with most questions left open-ended and responses not suggested. Abundant notes were taken but interviews were neither recorded nor transcribed. Not all questions could be asked to all respondents, depending on their available time. Each lasted between half to three hours, starting with informing respondents of the aim of the study while assuring anonymity and confidentiality, continuing on the topics listed in Table 1, and sometimes ending with a tour of the farm. Questions were neither pre-decided nor static. Instead, flexible guidelines determined during the landscape and historical phases were progressively refined. All structural and functional aspects that could potentially inform the organisation and reproduction of farming resources and activities were considered i.e. land, labour, production type and levels, equipment, working calendars, presence of particular activities, storage strategies, etc. Social and institutional conditions were included if relevant e.g. farming history, socio-demographics, rural context, etc. Questions were then oriented toward particular topics as their relative importance was determined. Other information typically included in farm surveys that were not deemed necessary for this study, according to the preliminary exploratory steps, were: education level, succession plans and operational specifics such as detailed herbicide use or frost management. Numerous prices and
costings were asked but income and other financial information was not collected aside from general questions about equity levels and debt situation. Most of the quantitative data collected was enriched with additional information, largely qualitative in nature, such as background events, constraints, anecdotes, personal experience, expected goals, etc. This allowed cross-checking values and assessing ranges, particularly for variables integrating long-term dimensions such as grain yields, field operations, livestock numbers. This was necessary as longitudinal data across several years was not recorded (no use of farm books or financial records). Instead, particular care was taken to obtain typical values representative of the most common range of situations encountered for the last 5-10 years, on which farmers would base their operations and anticipate results at the start of each agricultural cycle. Lows, highs and frequencies were asked to frame these typical values when time allowed. Although any topic could potentially be asked, attitudinal aspects were avoided. Answers were directed first and foremost toward facts and numbers through “when/what/who/how much” types of questions. “Why” and commentaries for given management choices were then regularly sought to contribute explaining their productive rationales, but practical reasons were preferably recorded rather than perceptions, views, opinions or preferences.

Table 1. Progression of semi-structured interviews with farmers: topics covered.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Questions</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Land</strong></td>
<td>Rainfall</td>
<td>Total, growing season</td>
</tr>
<tr>
<td></td>
<td>Location and boundaries</td>
<td>Map drawing</td>
</tr>
<tr>
<td></td>
<td>Area and status</td>
<td>Total, owned / leased / share-farming</td>
</tr>
<tr>
<td></td>
<td>Non arable land</td>
<td>Amount, type (rocky, bush, salt, wetland), uses</td>
</tr>
<tr>
<td></td>
<td>Arable area under each enterprise</td>
<td>Crops, pastures (in rotation/permanent, seeded or volunteer), varieties</td>
</tr>
<tr>
<td></td>
<td>Arable soil types and rotations</td>
<td>Amounts of broad soil types, location, additional descriptions;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>typical rotation composition and duration</td>
</tr>
<tr>
<td><strong>2. Crops</strong></td>
<td>Seeding priority</td>
<td>Soil or crop, seasonal conditions e.g. timing of first rains</td>
</tr>
<tr>
<td></td>
<td>Grain yields</td>
<td>Typical and range, variation per land type</td>
</tr>
<tr>
<td></td>
<td>Marketing</td>
<td>Type (pool, swaps, cash sales, grain broker), storage, presales,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>timings, buyers, lock-in prices, pricings</td>
</tr>
<tr>
<td><strong>3. Sheep</strong></td>
<td>Flock size and type</td>
<td>Maximum / typical, breed, reproduction / agistment / stud</td>
</tr>
<tr>
<td></td>
<td>Outputs</td>
<td>Wool, lamb/wethers age, pricing, weight, sales timing and buyers</td>
</tr>
<tr>
<td></td>
<td>Reproduction system</td>
<td>Ewes, fertility / mortality rates, offspring and cast for age per</td>
</tr>
<tr>
<td></td>
<td>Mob management</td>
<td>ewes, origin of male</td>
</tr>
<tr>
<td></td>
<td>Feed</td>
<td>Stocking rates, destocking priorities, flock movements</td>
</tr>
<tr>
<td></td>
<td>Cessation / continuation</td>
<td>Winter/summer: pastures, stubbles, stored grain, supplements,</td>
</tr>
<tr>
<td></td>
<td>Other animals</td>
<td>hay, priorities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reasons, date, future plans</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cattle, poultry etc.</td>
</tr>
</tbody>
</table>
### 4. History

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>Date, farm area, workforce and status at the time, origin (inheritance, bought, parents’ origin, land status, etc.)</td>
</tr>
<tr>
<td>Expansion</td>
<td>Dates, locations, reasons, paddock sizes</td>
</tr>
<tr>
<td>Major events</td>
<td>Re-fencing, policies, stopping sheep, new permanent worker, deep drainage, new rotation or machinery, prices, etc.</td>
</tr>
</tbody>
</table>

### 5. Workforce

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount and nature</td>
<td>Family, employees, seeding and harvest casuals (origin), partner's/children/parents occupations, non-farming activities, social activities e.g. associations</td>
</tr>
<tr>
<td>Needed equivalent</td>
<td>Whole farm/crops/sheep/finances/planning, current situation stretching/comfortable, ideal situation and constrains</td>
</tr>
<tr>
<td>permanent full-time</td>
<td></td>
</tr>
<tr>
<td>workers</td>
<td></td>
</tr>
<tr>
<td>Business status</td>
<td>Partnership (partners), trust, company</td>
</tr>
<tr>
<td>External advice</td>
<td>Agronomy/planning consultants beside input companies agents, farmer groups, others</td>
</tr>
</tbody>
</table>

### 6. Calendar

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dates/duration of operations</td>
<td>Crops: seeding, harvesting, spraying, spreading; sheep: lambing, muesling, sales, shearing</td>
</tr>
<tr>
<td>Peak/quiet periods</td>
<td>Activities (holidays, maintenance, fencing, replanting…)</td>
</tr>
<tr>
<td>Others</td>
<td>Stubble management (retention, narrow windrows, total burns, carts…)</td>
</tr>
</tbody>
</table>

### 7. Machinery

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>Overall: new/2nd hand, decision criteria for buying/renewing, timing, plans</td>
</tr>
<tr>
<td>Major machinery</td>
<td>Number, age, expected duration of use, width, capacity, shift duration for seeder (type of bar, knife-points, spacing, furrow type, depth), sprayer(s), harvester, tractors (hp)</td>
</tr>
<tr>
<td>Other machinery</td>
<td>Secondary tractors, spreader, mister, seed box, liquid cart, chaser bin, field bin, road-train, trucks, utes, loaders</td>
</tr>
<tr>
<td>Technologies</td>
<td>GPS guidance, auto-steer, controlled traffic, tram-lining, yield-mapped farm</td>
</tr>
<tr>
<td>Fixed equipment and buildings</td>
<td>Fuel tanks, fertilisers tanks, silos (seed, feed, storage), ogres, sheds, shearing sheds, workshop &amp; tools</td>
</tr>
</tbody>
</table>

### 8. Other expenses

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating</td>
<td>Machinery maintenance and repairs, fuel, power/water/rates, others</td>
</tr>
<tr>
<td>Fertilisers, herbicides and</td>
<td>Amounts on each crop and pasture (N, P, S, compounds/liquid, upfront/later, variable rate technology, conditions for variation</td>
</tr>
<tr>
<td>other sprays</td>
<td></td>
</tr>
<tr>
<td>Animals</td>
<td>Prophylaxis, shearing, muesling, fences</td>
</tr>
<tr>
<td>Wages</td>
<td>Staff, accountants, consultants</td>
</tr>
<tr>
<td>Others</td>
<td>Lime, insurance (crop/property), grants/levies</td>
</tr>
</tbody>
</table>

### 9. Banking

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall situation</td>
<td>Equity level, income tax level</td>
</tr>
<tr>
<td>Interest rates</td>
<td>Overdraft, core debt, machinery</td>
</tr>
<tr>
<td>Off-farm assets</td>
<td>Real estate, share portfolio, other business interests</td>
</tr>
</tbody>
</table>

### 10. Challenges and plans

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvements</td>
<td>Salinities issues, claying, other</td>
</tr>
<tr>
<td>Plans</td>
<td>Farm expansion, other</td>
</tr>
</tbody>
</table>

*Data input.* All the information collected was taken into consideration to determine the farming system typology and its key criteria, using the modelling process described above and in Fig. 3. However, not all the data was used to statistically assess dissimilarities between farming systems. Excluded variables were those for which: very
little variation was detected (e.g. business status, buildings, variable rate technology); no pattern emerged (e.g. interest rates, lambing dates, seeding rates); correlations were evident (e.g. barley yield to wheat); or not enough data points could be collected for all farming systems. Some of the qualitative information was coded using scales, generally from 1 to 5 where, when applicable, 1 represents high control/integration by the farm managers, and 5 reliance on external services. Rotation information was essential to define sub-systems according to the concepts of comparative agriculture (Fig. 4), but their long-term, flexible nature combined with farm soil heterogeneity prevented coding them into convenient variables. Their analysis was therefore kept separate.

The final dataset assessing statistical differences included absolute, relative and categorical variables, sometimes calculated, distinguished as follows:

- **Key variables (K):** typology criteria identified during the diagnostic to group farms into distinct farming systems.
- **Essential variables (E):** almost always included for their structural and functional importance, and likely to results in differences between farming systems (e.g. type of land and labour resources, farm enterprise mix, yields, animal numbers, main machinery, etc.).
- **Important variables (I):** for the characterisation of farming systems and/or likely to results in differences between farming systems (e.g. crop inputs, start of seeding), some of them identified as interviews progressed (e.g. nature of the family workforce)
- **Additional variables (A):** less likely to results in differences, but still potentially of interest (e.g. end of seeding, crop inputs)
- **Non-priority variables (N):** included mostly for their relevance to existing literature and local research (e.g. advisory services, equity level)

**Data quality.** The dataset was checked using qualitative information (e.g. individual context explaining atypical values, farm background to check ranges of values), cross-checking (e.g. using different variables to achieve the same calculations), and testing for expected correlations (e.g. area cropped/sprayer size). Data quality proved high, and the need to remove outliers exceptional (<1% from a dataset of ≈2000 values).

### 2.3 Effectiveness test: statistical differences between farm groups

The typology is composed of farming system types (i.e. models), each based on a given group of farms (Fig. 3). To test whether the typology effectively distinguished different farming systems, i.e. that are underpinned by different resources and processes, two aspects were tested.
First, differences in sub-system composition were demonstrated using a $X^2$ contingency table between observed and modelled values for farm enterprises mixes, which integrate variables representing the spatial and temporal organisation of land resources (Fig. 4). Modelled values at the farm level resulted from adding the areas under a given enterprise for each sub-systems, each of these area approximated by its proportion within rotations. For instance, a 4-year wheat-wheat-canola-pasture rotation typically implemented on a given type of soil corresponds to a cultural sub-system with an enterprise mix of 50% wheat, 25% canola, 25% pasture, to which an animal sub-system is associated in this study area (rare exceptions included cereals cut and sold for hay).

Second, farm group dissimilarities were assessed across the structural and functional variables described in the previous section using standard errors on means, and tested using non-parametric tests (one-way Wilcoxon-Mann-Whitney and Kruskal-Wallis, R Core Team (2015)). The same tests were applied to farm clusters (see section 2.5).

### 2.4 Extrapolation potential: defining classification rules

The typology and the identification of its key criteria required the in-depth investigation of the study area. To test whether these results could easily be extrapolated, i.e. used on other datasets which would not necessarily have the detailed information collected here about each farm, straightforward classification rules were defined based on the following requirements: (i) discriminating all the farming systems (matching farm groups without aggregation), (ii) using variables readily available from large-scale surveys, and (iii) remaining simple and convenient to be applied by a wide range of users. The resulting rules were applied on the original dataset, and the resulting farm groups compared with those on which the typology was based.

### 2.5 Performance test: comparison with multivariate procedures

Five multivariate cluster analyses were conducted to compare the similarities between farm groups determined empirically during the agrarian diagnosis (Fig. 5a), groupings produced by applying minimalist classification rules defined according to the resulting diagnostic (Fig. 5b), and farm clusters produced statistically with methods frequently used in farm typologies (Fig. 5c-h).

For this, Principal Component Analysis (PCA) and hierarchical Cluster Analysis (CA) were employed, with five procedural variations described in Table 2. These tools are well-known and commonly used in the characterisation of farm diversity and typologies (e.g. Iraizoz et al., 2007; Gaspar et al., 2008; Bidogeza et al., 2009; Choisis et al., 2012; Gelasakis et al., 2012; O’Rourke et al., 2012; Riveiro et al., 2013; Kuivanen
et al., 2016a). The procedures were particularly close to that employed by Riveiro et al. (2013) who also used a small dataset, notably regarding rules to choose which variables to include in the last two sets (Fig. 5.g-h, and which final number of clusters to keep. The two main differences were: (i) the possibility to retain variables with missing values by imputing, rather than averages, predictions that take into account links between variables and similarities between individuals (Josse & Husson, 2011, 2012), and (ii) no rotation of principal components (not necessary for the aims of this study). All procedures were performed with R 3.2.3 together with the packages psych, FactoMineR, missPCA, and dendextend (Lê et al., 2008; Galili, 2015; R Core Team, 2015; Revelle, 2015; Josse & Husson, 2016).

![Fig. 5. Grouping farms with different methods.](image)

Three types of procedures to group farms were compared: (a) empirical and iterative, using the farming system approach of the agrarian diagnosis (progressive definition of typology criteria using mixed methods); (b) a-posteriori and rule-based, using the results of the agrarian diagnostic (defining simple classification rules after a detailed analysis); and (c-h) a-priori and statistical, using multivariate cluster analyses (choosing criteria before conducting the statistical analysis, with several procedural variations).

PCA: Principal Component Analysis; PCs: Principal Components; CA: Cluster Analysis. * Variables typically collected by farm typology studies and in-depth surveys (see for instance references listed in section 2.5): set 1 and 2 thus gather distinct sets of variables, each a possible alternative to represent and potentially discriminate, in accordance with the aims of the work, the structural and functional characteristics of farms (Righi et al., 2011).
<table>
<thead>
<tr>
<th>Step and objective</th>
<th>Method and decision criteria (see studies listed in section 2.5 for further details)</th>
<th>Diag. 8 Var. (Fig.5c)</th>
<th>Diag. 2 PCs (Fig.5d)</th>
<th>Diag. 3 PCs (Fig.5f)</th>
<th>Set 2 (Fig.5gh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Statistical suitability</td>
<td>Step-wise variable selection and dataset corrections</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>1.1 Correcting for units effects</td>
<td>Data standardization (z-scores)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>1.2 Enough information provided</td>
<td>Variability measured with relative mean deviation from the mean (RMD) and relative standard deviation (RSD): both indicators &gt;25%</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3 Complete enough dataset</td>
<td>Remove farms and variables with missing values &gt;25%</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4 Information is not redundant</td>
<td>No simultaneous use of variables if their correlation coefficient &gt;0.8 (and Pearson p-value &lt;0.001)</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 Replacing missing values</td>
<td>Predictions using a regularized iterative PCA algorithm based on the number of dimensions estimated by Kfold cross-validation that minimises the mean square error of predictions</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>1.6 Sample adequacy for PCA</td>
<td>- Bartlett’s test of sphericity (p-value &lt;0.005)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>1.7 Kaiser-Meyer-Olkin test (KMO index &gt;0.5)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>2. Reduction of the multivariate information</td>
<td>Principal Components (PCs)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2.1 Method</td>
<td>Principal Component Analysis (PCA), no rotation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2.2 Selection of PCs</td>
<td>- Kaiser criterion (eigenvalues &gt; 1)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3. Clustering of farms</td>
<td>Hierarchical cluster analysis</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3.1 Distance matrix</td>
<td>Euclidian on farm scores for each retained PC</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3.2 Clustering method</td>
<td>Ward’s method</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3.3 Number of clusters</td>
<td>Dendrogram cut at the minimum height that achieves the highest group reduction and the fewest number of invalid groups (i.e. fewer than 4 farms, except if the group is only made of the 2 “Huge” outliers)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>5. Cluster evaluation</td>
<td>Differences between clusters</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>5.1 Statistical tests</td>
<td>Non-parametric tests on all variables available</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
3. Results

3.1 Overview of the study area

Overall, agricultural diversity in the study area was low, although no two farms were identical. With a few exceptions, all farms were thus: several thousand hectares; entirely mechanised with few labour units; heavily relying on chemical inputs (notably fertilisers and herbicides); dominated by rainfed cropping systems rotating wheat, barley, canola, and lupin seeded with no-tillage (knife-points); with/without sheep; run according to very similar calendars organised around one winter crop per year with seeding and harvest as peak periods for labour.

3.2 Farming system typology: 6 distinct groups, 2 major criteria

In spite of the low overall diversity, six distinct types of farming systems were identified (Fig. 6, Table 3). Almost all the farms in the sample (94%) were distributed between 4 of these farming systems, saved for the two largest farms. In spite of their uniqueness, these two farms could not be discarded as outliers once trends in size were identified. Farms could be allocated to the six farming systems on the basis of 8 key variables, summarised into 2 main criteria: farm size, and farm type. Very few borderline or intermediate farming situations were encountered. In these cases, allocation choices between farming systems were made on the basis of the recent farm history, such as business expansion or changes in workforce.

Farm type separated “mixed” crop/livestock farmers from “cropping specialists” (~60-42% of farms respectively) who did not normally implement sheep pastures on arable land (i.e. not part of rotations), and for whom livestock activities were absent or marginal (3 cases of opportunistic/temporary agistment, i.e. 8% of cropping specialists). Mixed farmers managed merino sheep flocks for wool and lamb, with a minority (10%) also producing meat with other breeds in dual-purpose flocks. Pastures covered a quarter of mixed farms on average, mostly volunteer grasses with some broadleaf weeds and a few seeded legume species.

Farm size was defined jointly by area, labour and machinery capacity (Fig. 7), differentiating “standard” (nearly 60%), “large” (40%) and “huge” (<3% i.e. 2 farms). All three farm sizes were encountered for both farm types, albeit with different values as mixed farms tended to cover areas 20-50% larger than those of cropping specialists. Exact transition thresholds from one size category to another were difficult to pinpoint, but more precise ranges could be defined using cropped area rather than total area (Table 3).
3.3 Effectiveness: 36 structural and functional differences identified

In spite of their many similarities, differences were found between farms grouped according to the farming system typology. These differences related to their organisation in terms of sub-systems, expressed by farm soil composition, rotations and resulting farm enterprise mix. Most of these sub-system differences were observed on heavily-textured soils, including the presence/absence of pastures and sheep (Table 4). Otherwise, differences were found for 36 of the 60 variables investigated (Table 5.a, Fig. 8). Some differences related to farm size irrespective of farm type, and vice-versa. Others were specific of given farming systems.

Differences were identified in nearly all the farming system aspects investigated, ranging from farm organisation (e.g. farm enterprise mix, field size) and resources (e.g. type and amount of labour available) to practices at field-level (e.g. crop management) and farm-level (e.g. machinery renewal and grain post-production strategies). For instance, compared to cropping specialists, mixed crop/livestock farmers had more diverse farm enterprise mixes, greater proportions of land presenting cropping difficulties, slightly lower typical farm wheat yields, and managed crops differently (more phosphate inputs, less sprays, less stubble retention). Mixed farmers were also older, had fewer dependents, and fuller working calendars due to animal activities.

When comparing farm sizes, all main productive farm resources differed i.e. land, labour and capital (off-farm and on-farm). This included shifts in machinery capacity occurring around 4 000 (“standard” to large”) and 7 000 (“large” to huge”) cropped hectares. Economies of scales were identified, with decreasing rates as farm size increased: standard, large and huge farms respectively cropped about 2 000, 2 300 and 4 000 ha per machinery unit on average. Compared to standard farms, large farms renewed their machinery quicker, often possessed a semi-trailer for transport, relied less on pool services for grain sales and storage, and made fuller use of the seeding window. These aspects were particularly pronounced among large cropping specialists.

Notable variables for which no differences were found between farming systems included manager experience (proxy: farming starting date), land tenure, farm fragmentation, off-farm work and equity levels, sheep production variables and nitrogen fertiliser use, spendings on advisory services (agronomy and planning), and seeding efficiency (≈20 ha seeded per pers. per foot of seeder).
Fig. 6. The six farming systems identified in the central Western Australian wheatbelt, defined by farm type and farm size.

Farm type opposed “mixed” system farms (combining both crop/pasture and sheep sub-systems) to “cropping specialists” (cropping sub-systems only, i.e. no pasture in rotation). Farm size was represented here using arable area (ha) and machinery capacity (width), although labour variables were taken into account and could be used as well (FTE = Full-Time Equivalent). Percentages relate to the proportion of respondents in the sample for each farming system (total n=36, ≈half the farms of the 4 000 km² study area). Ranges of existence for “huge” systems are only tentative, given the uniqueness of their situation. Two farms implemented “standard” size systems but were too small to generate a full income and relied on off-farm activities.

Linear regression with arable area: adj. R²
Machinery capacity (unit, this graph) 0.71
Labour present all year (FTE) 0.68
Labour present at seeding (FTE) 0.82
Labour present at harvest (FTE) 0.89
(all p<0.001)
Table 3. Farming system typology: typical characteristics and relative importance.
Each farming system is a modelled representation simplifying the varied situations of a group of individual farms.

<table>
<thead>
<tr>
<th>Farm size</th>
<th>Farm type</th>
<th>Standard</th>
<th>Large</th>
<th>Huge</th>
<th>Sample average (observations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arable area (ha)</td>
<td>Standard</td>
<td>2 000</td>
<td>2 500</td>
<td>5 000</td>
<td>7 500</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>[1 000* - 3 500]</td>
<td>[1 500* - 8 000]</td>
<td>[5 000 - 10 000]</td>
<td>[8 000 - 13 000]</td>
</tr>
<tr>
<td></td>
<td>Huge</td>
<td>2 000</td>
<td>2 000</td>
<td>5 000</td>
<td>6 000</td>
</tr>
<tr>
<td>Cropped area (ha)</td>
<td>Standard</td>
<td>2 000</td>
<td>2 000</td>
<td>5 000</td>
<td>6 000</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>[1 000* - 3 500]</td>
<td>[1 500* - 8 000]</td>
<td>[5 000 - 10 000]</td>
<td>[8 000 - 13 000]</td>
</tr>
<tr>
<td></td>
<td>Huge</td>
<td>2 000</td>
<td>2 000</td>
<td>5 000</td>
<td>6 000</td>
</tr>
<tr>
<td>Machinery units</td>
<td></td>
<td>1.0 u.</td>
<td>1.6 u.</td>
<td>2.7 u.</td>
<td>1.4 u.</td>
</tr>
<tr>
<td></td>
<td>Standard</td>
<td>[0.8 - 1.2]</td>
<td>[1.2 - 2.3]</td>
<td>-</td>
<td>[0.8 - 3]</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>40, 35, 100</td>
<td>65, 55, 160</td>
<td>110, 80, 270</td>
<td>55, 45, 130</td>
</tr>
<tr>
<td></td>
<td>Huge</td>
<td>360</td>
<td>520</td>
<td>900</td>
<td>2</td>
</tr>
<tr>
<td>Seeder, sprayer, header (ft)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>2+2</td>
<td>1+1.2</td>
</tr>
<tr>
<td>Head tractor (hp)</td>
<td></td>
<td>2+0</td>
<td>2+0</td>
<td>2+5</td>
<td>2+5</td>
</tr>
<tr>
<td>Semi-trailer (number)</td>
<td></td>
<td>0</td>
<td>0.5+0.5</td>
<td>2+2</td>
<td>2+2</td>
</tr>
<tr>
<td>Labour, permanent (FTE)</td>
<td></td>
<td>2 [1-2.5]</td>
<td>2 [1-3]</td>
<td>2.5 [2-3]</td>
<td>3 [2.5-5]</td>
</tr>
<tr>
<td>Permanen, (FTE) family + employee</td>
<td></td>
<td>2+0</td>
<td>2+0</td>
<td>1.5+1</td>
<td>2+1</td>
</tr>
<tr>
<td>Casual labour (FTE) seeding + harvest</td>
<td></td>
<td>0+0</td>
<td>0.5+0.5</td>
<td>2+2</td>
<td>0+2</td>
</tr>
<tr>
<td>Flock (reproducing ewes)</td>
<td></td>
<td>-</td>
<td>500 - 2 000</td>
<td>- 1 000 - 3 000</td>
<td>- &gt; 3000</td>
</tr>
<tr>
<td>In study area: % farms</td>
<td></td>
<td>20</td>
<td>38</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>(approx.) % area</td>
<td></td>
<td>10 22</td>
<td>25 36</td>
<td>3 4</td>
<td>45</td>
</tr>
</tbody>
</table>

* Lower farm sizes require off-farm income from the main manager.

Notes: arable area = 90% total farm area; FTE: Full-Time Equivalent; shifts in size occur between: 3 000 - 4 500 cropped ha (“standard” to “large” farms) and 6 000 - 9 000 cropped ha (“large” to “huge” farms).
Fig. 7. Farm size defined jointly by cropped area, permanent labour, machinery capacity.

Farm frequency distributions (n=36) for each variable are represented through histograms (bars) and kernel densities (curves). Individually, neither of the 3 variables evidently segregates into distinct groups. The multimodal distribution resulting from 3 distinct sub-populations of farm sizes becomes more apparent when all 3 variables are considered together, as illustrated with a simple additive index. Other variables reinforce these results, for instance hired casuals, presence/absence of specific machinery, assets, etc. Using total arable area instead of cropped area also permits to identify 3 populations.
Table 4. The four cultural sub-systems identified and their localisation per soil type and farm type.

<table>
<thead>
<tr>
<th><strong>Cultural sub-systems (crops with or without pastures)</strong></th>
<th><strong>Typical rotation (years)</strong></th>
<th><strong>Resulting typical enterprise composition (%)</strong></th>
<th><strong>Associated soil type and presence (% total farm area)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cereals</td>
<td>Break crops</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light</td>
<td>Medium</td>
</tr>
<tr>
<td>A (3.5 years): 2-3 cereals + 1 break crop</td>
<td></td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>B (4.5 years): 3-4 cereals + 1 break crop or fallow</td>
<td></td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>C (3.5 years): 2-3 cereals + 1 break crop or pasture</td>
<td></td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>D (3 years): 2 cereals + 1 pasture</td>
<td></td>
<td>65</td>
<td>0</td>
</tr>
</tbody>
</table>

**Farm area under each enterprise (%):** observed average / modelled

- **Cropping specialists:** 76 / 72 - 21 / 26 - 3 / 2
- **Mixed crop/sheep:** 65 / 68 - 12 / 12 - 24 / 20

1 For instance, rotation A can correspond to Wheat/Wheat/Barley/Canola (4 years, 75% cereals, 25% break crops) or Wheat/Wheat/Lupin (3 years, 65% cereals, 35% break crops).
2 The two farm types have different amount of each soil type, to which specific sub-systems are associated. Cropping specialists have more light sandy soils and typically implement a combination of A-B sub-systems, whereas mixed crop/livestock farmers have more heavily-textured soils and implement a combination of A-B sub-systems, whereas mixed crop/livestock farmers implement a combination of A-C-D, with the last two sub-systems associated with a sheep sub-system (variations were encountered e.g. in production levels, lambing, fertility rates, but no distinct pattern permitting to differentiate sheep sub-systems). The two “huge” farms were excluded from the data presented here. The spatial influence of land heterogeneity on rotation practices was further demonstrated in Lacoste et al. (2016), with linkages established between farm soil composition, farm location, farm type and farm grain yields.
3 Modelled farm area (%) under each enterprise = Σ(cultural sub-systems) composition × presence on farm

3.4 Classification rules: groups match the farming system typology

For application by most databases, three nested rules were defined to classify farms that summarised the 8 key variables composing the two criteria of the typology. The first rule related to the presence/absence of pastures of rotation, the other two to farm size. As shown in Fig. 9.b, applying these rules to the dataset of the sample led 35 of the 36 farms (97%) to be correctly classified according to the typology definitions. Modifying the first rule to “stocking rates < 0.1 sheep/arable ha” was as effective, although the one mis-classified farm was different.
3.5 Performance: typology groups are more distinct than multivariate clusters

As shown at the end of Table 5.a, the farming system typology used only 8 defining variables as a basis for segregation which led a total of 30 variables to significantly differ between groups (p<0.05), with a further 6 variables showing trends of interest (p<0.1). This corresponded to all the variables that had been identified as “key” and used as criteria, three quarters of the 34 variables that had been identified as “essential” and “of interest”, but to only 3 of the 18 “additional” and “non-priority” variables.

In comparison, the five multivariate clustering procedures, using the same 8 defining variables or larger sets of 16, resulted in farm clusters that differed across fewer variables (11 to 19 at p<0.05, 17-26 at p<0.1, Table 5.b). Furthermore, cluster number and composition varied greatly (Fig. 9.c-g), showing the impact of choosing different “potentially discriminating variables” and/or the impact of relatively small protocol changes (i.e. using slightly different criteria to define the number of principal components, as encountered across the studies listed in section 2.5). Clustering results were best (in terms, again, of the number of significantly different variables) when applied to the key variables identified during the agrarian diagnosis without preliminary reduction via principal component analysis (Fig. 9.c).

Table 5. The 60 variables extracted from the interviews and included in the analysis. Comparison of the farm groups produced by using different methods (see descriptions Fig.5 and Table 2). The groups were more distinct (i.e. differed across more variables) when obtained using the criteria defined during the agrarian diagnosis (a) than any of the statistical procedures (b). The details of notable variables are plotted in Fig. 8.

| Variable (units) | Sample: Nh Mean ± s.e. obs | Differences between:
| | a) Diagnostic groupings (number) (Fig.5a) | b) PCA/CA clusters (number) |
| | Plot Var. Size Type FS Fig. type (2) (4) | Diag. 8Var (4) (Fig.5c) | Diag. 2PCs (3) (Fig.5d) | Diag. 3PCs (4) (Fig.5f) | Set. 1 (6) (Fig.5g) | Set. 2 (3) (Fig.5h) |
| **1. Farm size** | | | | | |
| Arable area (ha) | 34 4030±387 | a K+ ^ *** ns *** | ✓ *** ✓ *** ✓ *** * ✓ ✓ |
| Machinery capacity (1 unit = 40 ft. seeder + 35 ft. harvester) | 34 1.3 ± 0.07 | a K+ *** ns *** | ✓ *** ✓ *** ✓ ** * - x * |
| Permanent workers, family and employees (FTE) | 34 2.3 ± 0.2 | K+ ** ns ** | ✓ ** ✓ ** ✓ * x ns ns |
| Flock (number of reproducing ewes) | 34 849±147 | E ns *** *** | * ns * ns ✓ ns |

Table 5.a: The farming system typology used only 8 defining variables as a basis for segregation which led a total of 30 variables to significantly differ between groups (p<0.05), with a further 6 variables showing trends of interest (p<0.1). This corresponded to all the variables that had been identified as “key” and used as criteria, three quarters of the 34 variables that had been identified as “essential” and “of interest”, but to only 3 of the 18 “additional” and “non-priority” variables.
### 2. Farm organisation

<table>
<thead>
<tr>
<th>Enterprise diversity index</th>
<th>33 0.46 ± 0.02</th>
<th>b E - - *** *** * ns * ns × ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arable area under cereals (%)</td>
<td>34 68 ± 2</td>
<td>b E ** *** *** * * ns * ns × ns *</td>
</tr>
<tr>
<td>Arable area under pastures (%)</td>
<td>20 24 ± 3</td>
<td>c K+ * - - ✓ - ✓ ns ✓ - ✓ ns •</td>
</tr>
<tr>
<td>Improved pastures (%)</td>
<td>20 25 ± 6</td>
<td>c E - - - • - • ns ns</td>
</tr>
<tr>
<td>Field size (ha)</td>
<td>24 111 ± 10</td>
<td>d I * *** *** * ns * ns × *</td>
</tr>
<tr>
<td>Fragmentation ratio (area within which the farm is contained)</td>
<td>33 2.2 ± 0.2</td>
<td>d N ns ns ns ns ns ns ✓ ** ns</td>
</tr>
<tr>
<td>Terminated sheep production (date)</td>
<td>12 2002 ± 2</td>
<td>A ns - - - - - -</td>
</tr>
</tbody>
</table>

### 3. Farm resources

| Non-arable and arable rocky (%) total area | 33 20 ± 4 | e E ns * ns ns ns ns ✓ ns * |
| Heavy-textured and/or sloping land (%) arable area | 33 51 ± 6 | e E ns ** • ns ns • • ✓ • |
| Family workers (%) permanent FTE | 34 77 ± 4 | f K+ ** ns * ✓ * ✓ *** ✓ ** ns ✓ * |
| Previous generation workers (%) family FTE | 34 49 ± 6 | f I ns * ns ns ns ns ns |
| Casual workers at seeding (%) FTE present at seeding | 34 23 ± 4 | g K * ns * ✓ *** ✓ *** ✓ *** ns ✓ * |
| Casual workers at harvest (%) FTE present at harvest | 34 27 ± 4 | g K *** ns ** ✓ *** ✓ *** ✓ *** ✓ ns * |
| Off-farm real estate (number of owned houses) | 26 1.0 ± 0.2 | h I * ns ns ** * * * ✓ ns * |
| Off-farm asset diversity (real estate, share portfolio, business interests) | 26 1.4 ± 0.2 | h I * • ns * • * * ns ✓ ** |
| Equity level (%) approximated from ranges | 26 82 ± 2 | N ns ns ns • ns • ✓ ns ✓ * |
| Land leased (%) arable ha | 33 11 ± 4 | N ns ns ns ns ns ns ✓ ns ✔ |

### 4. Workloads and calendars

<p>| Arable area per permanent worker (ha/FTE) | 33 1720 ± 132 | i K *** ns *** ✓ *** ✓ *** ✓ *** ns ✓ ** |
| Seeded area per worker present at seeding and per seeder width (ha/FTE/feet) | 33 21 ± 1.0 | i E ns ns ns ns ns ns ✓ * ns |
| Start of seeding (date) | 31 24th ± 1 Apr. | j I • • ns • • • ns ✓ ns |</p>
<table>
<thead>
<tr>
<th>End of seeding (date)</th>
<th>j</th>
<th>A</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
<th>ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of seeding (week)</td>
<td>k</td>
<td>I</td>
<td>•</td>
<td>ns</td>
<td>ns</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Seeder shift (hour used/day)</td>
<td>l</td>
<td>I</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>*</td>
<td>ns</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Off-peak winter-spring period (month)</td>
<td>m</td>
<td>I</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Off-peak summer period (month)</td>
<td>n</td>
<td>I</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

### 5. Grain production

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Wheat yield (t/ha) | 30 | 2.0 ± 0.05 | m | E | ns | • | ns | ns | ns | ns |
| Canola yield (t/ha) | 15 | 1.00 ± 0.04 | m | A | ns | ns | ns | ns | ns | x |
| Total phosphate applied to wheat (u./ha) | 25 | 6.7 ± 0.3 | n | I | ns | * | • | * | I | ns |
| Total nitrogen applied to wheat (u./ha) | 27 | 40 ± 3 | I | ns | ns | ns | ns | ns | ns | ns |
| Minimum nitrogen applied to wheat (u./ha) | 20 | 30 ± 3 | I | ns | ns | ns | ns | ns | ns | ns |
| Maximum nitrogen applied to wheat (u./ha) | 20 | 49 ± 4 | I | ns | ns | ns | ns | ns | ns | ns |
| Basal nitrogen applied to wheat (u./ha) | 23 | 20 ± 2 | A | ns | ns | ns | ns | ns | ns | ns |
| Top-up nitrogen applied to wheat (u./ha) | 23 | 20 ± 2 | A | ns | ns | ns | ns | ns | ns | ns |
| Use of liquid nitrogen (1: 30 | 2.6 ± 0.2 | n | I | ns | • | ns | ns | ns | ns | ns |
| In-crop herbicides and other pesticide sprays ($/ha) | 22 | 55 ± 2 | o | A | ** | * | ** | I | ns | ns |
| Controlled traffic (1: none, 3: auto-steer only, 5: all tramlined) | 27 | 2.6 ± 2 | A | ns | ns | ns | ns | ns | ns | ns |
| Stubble management (1: all burn, 3: narrow windrow, 4: cart: 5 retained, mowed) | 22 | 3.1 ± 0.2 | o | A | ** | * | ** | I | ns | ns |
| Advisory services, agronomy & farm planning ($/ha) | 29 | 0.83 ± 0.17 | N | ns | ns | ns | ns | ns | ns | ns |

### 6. Animal production (mixed farmers only)

| Sheep stocking rates (reproducing ewes/ha of pastures) | 20 | 1.6 ± 0.2 | p | E | ns | - | ns | - | ns | x |
| Fertility rates (%) | 17 | 91 ± 3 | E | ns | - | - | ns | - | ns | x |
| Wool production (kg/ewe) | 20 | 9.5 ± 0.9 | p | E | ns | - | ns | - | ns | x |
| Lamb/wethers sale age (month) | 20 | 9.1 ± 0.7 | A | ns | - | - | ns | - | ns | ns |

### 7. Management strategies

| Seeder turnover rate (1: fast, to 5: slow) | 34 | 4.0 ± 0.2 | q | E | - | ns | - | * | ns | ns |
| Harvester turnover rate (1: fast, to 5: slow) | 34 | 3.2 ± 0.3 | q | E | ** | ns | - | * | ns | ns |
Grain sale strategy (1: private deals, to 5: reliance on pool prices)  31 3.4 ± 0.2
Grain price monitoring (1: hired broker, to 5: reliance on pool)  31 2.5 ± 0.2
Grain carting field to bin, and freight bin to port (1: both by farm, to 5: both contracted) 32 3.2 ± 0.2
Semi-trailers (number)  33 0.4 ± 0.1
Grain storage (1: on-farm, to 5: off-farm) 32 4.5 ± 0.2
Expansion, planning to (1: no, to 5: yes) 10 29 3.3 ± 0.3
Expansion, main constraint (1: labour, to: 5 capital) 11 29 3.6 ± 0.3
Farming start of the family in the area (date) 12 27 1920 ± 4
Farming start of the current manager (date) 33 1986 ± 2
Manager life cycle stage (1: <35 year old typically no children, to 5: with adult children or nearing retirement) 31 3.1 ± 0.2
Dependents ratio (children per family FTE) 27 1.3 ± 0.2

8. Social circumstances

<table>
<thead>
<tr>
<th>Defining variables</th>
<th>any: 8 7 1 8 8 8 16 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farming start of the family in the area (date)</td>
<td>u A ns ns ns ns ns * ns ns</td>
</tr>
<tr>
<td>Farming start of the current manager (date)</td>
<td>u A ns ns ns ns • ns ns ns</td>
</tr>
<tr>
<td>Manager life cycle stage</td>
<td>v I ns • ns ns ns ns ns * ns</td>
</tr>
<tr>
<td>Dependents ratio</td>
<td>v I ns * ns ns ns ns ns ns ns</td>
</tr>
</tbody>
</table>

Explained differences:
- at p<0.01 (**,***)
  any:15 10 7 7 9 7 8 3 3
- at p<0.05 (**,**,**,**)
  any:30 22 14 15 19 12 19 11 12
- incl. trends of interest at p<0.1 (*,**,**,**)**
  any:36 25 20 20 22 17 26 16 20

PCA details

<table>
<thead>
<tr>
<th>Farms included:</th>
<th>36 36 36 33 34</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variables considered / retained:</td>
<td>8 / 8 8 / 8 8 / 8 23 / 16 26 / 16</td>
</tr>
<tr>
<td>PCs retained:</td>
<td>n.a. 2 3 6 6</td>
</tr>
<tr>
<td>Missing values predicted (%):</td>
<td>0.3 0.3 0.3 5.5 6.3</td>
</tr>
<tr>
<td>Bartlett</td>
<td>n.a. &lt;0.00 &lt;0.00 0.04 &lt;0.00</td>
</tr>
<tr>
<td>KMO</td>
<td>n.a. 0.58 0.58 0.56 0.55</td>
</tr>
<tr>
<td>Cumulated variance explained (%)</td>
<td>n.a. 75 87 71 76</td>
</tr>
</tbody>
</table>

1 p-values: *** <0.001, ** <0.01, * <0.05, • <0.1, n.s. >0.1., - not tested (not applicable to all groups).

Tests for the rule-based groupings (classification) are not shown due to a 97% similarity with the typology. Underscores indicate results significant at 5% from variables that were not included/retained in the definition of the farm groupings (diagnostic and clustering). “Huge” farms (only 2 observations) were included in the cluster analysis (see Fig. 9) but not in the tests for differences nor in the sample information.
a) Variable type: K+: key typology criteria (^:proxy also used for the rule-based classification); K: other key variables used to refine the typology; E: Essential variables; I: Important variables identified; A: Additional variables of possible interest; N: Non-priority variables.

Groups: Size: “Standard” vs. “Medium”; Type: “Mixed” vs. “Croppers”; FS (Farming Systems): “Standard Mixed”, “Standard Croppers”, “Medium Mixed”, “Medium Croppers”. See Fig. 6 and Table 3 for definitions: farm size is defined by area, machinery and labour; farm type is defined by the presence or absence of actual pastures i.e. in rotation with crops, not necessarily by that of sheep, which cropping specialists may agist on fallows and marginal land.

b) ✓: variable considered but not included due to statistical unsuitability (see Table 2); ✗: included in analysis. With 1 exception (area under pasture in Diag.2.PCs), all these included variables showed high contribution to at least one of the retained PCs (|score| > 0.4; data available from the authors).

The 20 observations and sample values refer to mixed farmers only. For clustering, 0 were included for cropping specialists.

All values are typical, i.e. represent the most common situation encountered by farmers unless otherwise indicated. FTE: Full-Time Equivalent worker, which includes unofficially employed or on-call family workers (spouse, parents or children for bookkeeping, seasonal work, casual help, etc.).

Adapted from Simpson diversity index $D = 1 - \sum p_i^2$ where $p_i$ is the proportion of farm area typically under enterprise i, here cereals (wheat, barley, rarely oat), oilseeds (canola), legumes (lupin, improved pastures i.e. clover and serradella, rarely peas) and grasses (mostly volunteer pastures, some chemical fallows).

The three main arable land types on farm are: light sandy to gravelly soils (which dominate on sandplains), sandy clays and loams (which dominate in valley floors), and medium soils (varied intermediate-textured situations). Farmers implement flexible but distinct crop/pasture rotation on each soil type (different durations and enterprise successions). See Table 4 and Lacoste et al. (2016) for further details.

Family workers who started farming before 1985 (average date managers in the sample started farming).

Results are similarly not significant when calculations include duration (sample average: 3.5 ±0.3 seeded ha/FTE/feet/week; approx. 0.03 seeded ha/FTE/feet/day).

Excludes accountants and sale brokers. In the sample, 52% of managers employ agronomy/farm planning consultants (spending 3 000 to 11 000 AU$/year), 10% rely on farmer groups only (<1 000 AU$/year), and 38% do not commit spendings on this type of advice.

Machinery turnover strategies typically fall in 3 classes: "fast" when new machinery is replaced in less than 5 years with high costs compensated by substantial tax savings; "standard" when machinery is bought new or almost new and kept for 5-10 years (or longer for seeders), and "slow" when machinery is typically bought second hand and/or maintained to last over 10-15 years.

Expansion plans: the value of 5 includes respondents who had only just expanded.

Expansion constraints: 40% of respondents did not specify a constraint and/or mentioned land shortages (intermediate value of 3). Capital constraints refer to difficulties in securing a bank loan to purchase land and/or upgrading machinery capacity. Labour constraints usually refer to already stretched family capacity and/or the difficulty in sourcing reliable permanent employees.

Farms are family-managed (2 exceptions with hired managers) and family-inherited (1 corporate exception), all founded by English-speaking Western Australian, interstate and overseas migrants: 77% were founded during pioneering times (1910s), 6% post-WWII (1950s), 6% during the call for UK migrants (1970s), and 10% in recent times (1990s-2010s).

Elderly parents at charge were included when mentioned, but most dependents were young children at home or boarded teenagers. The former incurs high caring costs that typically limits the spouse involvement in farming activities (low availability of rural services), the latter high financial costs and specific care periods (school holidays).
Fig. 8. Structural and functional differences between farming systems.
Details about the variables noted # are available in Table 5.
Fig. 9. Comparison of farm groups produced by applying different methods on different sets of structural and functional variables

a) Symbols represent the allocation of a given farm to a farming system as determined during the agrarian diagnosis (n=36). Alternative farm groups (dashed grey rectangles) are produced by: b) applying 3 simple nested rules that were defined from the diagnosis results and that are readily applicable by census and large-scale surveys; c) clustering on the key variables used during the diagnosis; d) and e) idem, with the prior reduction of the multivariate information into principal components (PCs); f) and g) principal components analysis followed by cluster analysis as well, on two different sets of variables that each matches the objectives of the study and are routinely recorded by surveyors.
4. Discussion

The tools of comparative agriculture, originally built for developing country situations (Cochet, 2015), permitted the diversity of farming systems in a broadacre region to be assessed.

In spite of farm productions and practices being overall little diversified, dissimilarities between farm types were shown across a wide range of structural and functional variables, both absolute and relative, covering farm resources, practices, strategies, as well as some production levels and social circumstances. Distinctions were further demonstrated by identifying different farm soil profiles and cultural sub-systems (notably detected through specific crop and pasture rotations on different land types) which combination translated in different farm enterprise mixes. Importantly, simple rules could be defined for non-specialists users to conveniently extrapolate and apply the typology, with examples provided by Valbuena et al. (2008) and Riveiro et al. (2008) in other contexts.

These results have numerous implications and applications for farming system knowledge in Australia, as regional pictures of farm and practice diversity had not been produced at this level of detail before. For instance, the study demonstrated that different farming systems co-exist within an area and showed that, superseding variations in individual choices and circumstances, pragmatic differences in land and labour resources are associated with farm structure and functioning (e.g. presence of sheep, crop management practices, machinery renewal, grain post-production strategies, etc.). Here, discussion focusses on: the performance of the comparative agriculture framework in relation to the specific objectives of this study compared with the multivariate methods commonly used to construct farm typologies; how information was obtained to permit these results; and in what respect the original concepts of comparative agriculture contributed to the procedure. Notes are also made about the place comparative agriculture typologies hold within current approaches.

4.1 Analytical choices: favouring the progressive selection of relevant criteria over linear statistical processing

The empirical procedure of comparative agriculture performed better than multivariate clustering techniques, producing groups of farms that were more distinct, i.e. that differed across a larger number of variables than statistical farm clusters (Table 5). This was the case even when the criteria used were the same as those of the typology.
Those results are important because most quantitative studies on farming diversity employ a variation of the multivariate clustering methods tested here. Alternatives exist (e.g. Riveiro et al., 2008; Valbuena et al., 2008; Righi et al., 2011; Stott et al., 2013; Kuivanen et al., 2016b), however cluster analysis preceded by Principal Component Analysis (or similar) is a procedure that dominates the published literature on the topic and is regularly hailed as best practice to produce farming typologies (Emtage & Herbohn, 2012). Numerous studies have showed that these statistical techniques can indeed be suitable as data-mining tools for broad-picture classifications at large scales (e.g. Iraizoz et al., 2007; Surendran Nair et al., 2016), and when the criteria are pre-defined, for typologies built for specific objectives, for attitudinal profiles, and for market segmentation type of studies (e.g. Blazy et al., 2009; Greiner et al., 2009; Waters, 2009; Sherren et al., 2011; Emtage & Herbohn, 2012; O'Rourke et al., 2012; Blanchard et al., 2013; Kingwell et al., 2013; Hyland et al., 2015). However, the relevance of multivariate clustering techniques to assess regional diversity in terms of farming systems is much less documented. The study of Kuivanen et al. (2016b) is a rare exception, highlighting the sensitivity of statistical typologies to data quality. Here, limitations were shown even when the same dataset was used, further confirming that caution should be exercised. The shortcomings of multivariate clustering techniques for farming system studies can be explained by analytic choices relating to the nature of statistical clustering, to the linearity of protocols, and to the choice of defining variables.

Farm clusters are formed by maximising differences between groups on a statistical basis, which depends on the procedure and criteria chosen, and does not necessarily coincide with the functional rationale of farming systems. Cluster number and composition can thus vary greatly with procedural changes, as exemplified here. Yet, cluster stability, robustness or predictive abilities are rarely tested or discussed. Surendran Nair et al. (2016) achieved this but required large scales and datasets that are seldom available.

Statistical clusters may thus be mathematically optimal but make little logical sense, particularly when variables are chosen arbitrarily. Yet, this represents the mainstream practice in farming diversity studies. Analytical procedures are linear, with defining variables chosen by design prior to the study, farming groups constructed by the statistical analysis, then the mechanisms composing the farming systems subsequently interpreted. In some cases, the choice of variables is guided by pilot phases, but typically those steps are very briefly described and rely on local expert knowledge or the informal experience of the investigators. Tittonell et al. (2005; 2010), Girard et al. (2008), Choisis et al. (2012) and Blanchard et al. (2013) provided counter-
examples where productive processes and sub-systems were determined with field investigations prior to conducting multivariate clustering. More commonly however, variables that are “likely” or can “potentially” discriminate farms are chosen among those already available, convenient to collect, or of potential interest considering the findings of other studies. In addition, some variables are always informed without questioning their relevance (or their definition, that may differ between countries). A consequence is that basic structural, socio-economic and financial indicators such as farm size, farmer education, household income, total factor productivity, tax-declared labour units and operating profit are much more commonly included than those describing generational ratios, machinery renewal strategies or seeding windows, like it was the case here. In fact in this study, few variables recommended by existing literature and local research proved distinct across farming systems.

In addition, farming variables deemed standard or sourced second-hand can present further drawbacks in multivariate cluster analysis, particularly when originally collected for other purposes. For instance, production records and financial indicators of government census and consultant surveys may not be relevant for statistical typologies. The accuracy of the data can also be highly questionable (Carletto et al., 2013). Besides unknown biases and inconsistencies, these drawbacks include issues with capturing long-term dynamics, difficulties in distinguishing processes behind aggregated indicators, and artificial trends resulting from arbitrary discretisation (e.g. classes of farm areas or financial returns) (Iraizoz et al., 2007; Pradeleix et al., 2012; Kingwell et al., 2013; Kuivanen et al., 2016b). For instance in Australia (e.g. ABARES, 2016), the typical segregation of farms in size and activity classes according to financial thresholds does not account for the multi-modal distributions of physical resources and the variation in farming practices identified here. Issues exist even when variables are kept continuous, as statistical optimisation may questionably prioritise some variables over others. For instance, near-zero values may be either emphasized or overlooked depending on how contrasted the other variables are. Here, a few hundred sheep may correspond to negligible opportunistic husbandry rather than full-fledged animal sub-systems, a difference not necessarily made by clustering.

To compensate for these pitfalls, and more generally to address the uncertainty in choosing valid criteria among the multitude of variables that can potentially describe the complex processes at play, large numbers of defining variables may be included in hope of achieving exhaustivity. Ordination methods, typically Principal Component Analysis, can then help with data redundancy but may also result in a hierarchisation of factors favouring statistical contrasts rather than productive rationales. For instance here, Principal Component Analysis mostly worsened clustering results, probably
because of the low degree of agricultural heterogeneity in the Western Australian wheatbelt (e.g. very similar farm enterprise mixes, production types and levels, equipment, crop operations). Weighting variables may help, but information to do so adequately is usually lacking without conducting detailed investigation beforehand (Choisis et al., 2012).

In contrast, analytical choices in comparative agriculture methods are made progressively and empirically, throughout the agrarian diagnosis which allows for feedbacks. The relevance of defining variables and segregating criteria is not derived a priori from local expert knowledge or from the literature, but determined during an iterative, in-depth, multi-disciplinary investigation grounded in direct observations. In comparative agriculture, the analytical process used to assess farming diversity thus cannot be dissociated from applied field work.

4.2 Methodological tools: overcoming practical issues that prevent applied, holistic farming system studies

The methods of comparative agriculture heavily depend on the ability to capture large amounts of information sourced first-hand about a wide range of farming system aspects. Applied studies integrating the multi-faceted aspects of farming systems are rarely conducted because of the difficulty to source detailed, quality data in sufficient quantities that is representative of the farming population studied. In this study, data scarcity challenges were solved cost-efficiently, and holistic and representation requirements were met, using a specific mixed methods procedure. Importantly, the use of qualitative and quantitative methods was not sequential (e.g. qualitative pilot phase followed by quantitative survey), but concurrent for both data collection and analysis. This permitted to accommodate a range of requirements that could not be fulfilled by either research type on its own (Plano Clark & Ivankova, 2016). Furthermore, the originality here is not intrinsically due to both quantitative and qualitative type of data being used, since various statistical tools exist that allow the integration of both in multivariate clustering techniques (e.g. Blazy et al., 2009; Choisis et al., 2012). The distinction with most studies on farming diversity is methodological: quantitative data clearly constituted the basis of the agrarian diagnostic, but crucial improvements were provided throughout the procedure by techniques that are usually associated with qualitative procedures. As such, the agrarian diagnostic provides a relatively rare illustration of the practical benefits (and possibility) of considering qualitative and quantitative paradigms as part of a continuum rather than being mutually exclusive (Makrakis & Kostoulas-Makrakis, 2016).
Firstly, the iterative nature of the diagnosis ensured a holistic perspective by systematically covering a wide range of farming system aspects, including geographical (landscape analysis), social and institutional (historical investigation), agronomic (current practices), technical and economic (performances). Procedural flexibility was an essential part of this, allowing investigating varied avenues but only in so far as they inform the analysis, and permitting to go back to locations of interest and to respondents for clarifications and verifications when necessary. Importantly, flexibility did not equate procedural mayhem. In fact, each step of the diagnosis was carried out in a specific order, the completion of each step validating the results of the previous one through a feedback process, and informing what should be asked during the next. Determining homogenous landscape zones thus provides a basis on which historical aspects can be anchored, which in turn, assuming either continuity or discontinuity in practices, informs questions about the current situation. For instance in this study, determining major soil types provided spatial units to determine crop rotations with retired farmers, both later refined with current managers. Similarly, identifying the mechanisms underlying farming systems before their performances allows prioritising the collection of pricing and costing information. This empirical process of constant verification and progressive prioritisation permitted to cost-efficiently manage two crucial issues: one relates to unknown levels of heterogeneity in the study area, which determines the level of details to be retained (the more diverse and complex the systems, the more data is required for their description); the other issue relates to the number, nature and relative importance of factors discriminating farming systems not being known in advance, that require a hierarchisation. Only once both are known, can adequate variables be selected (and if relevant, their discretisation achieved adequately).

Secondly, the importance given to exploration and to the investigative reconstitution of events contributed to a range of practical considerations. Incidentally, these two techniques are little used in Australian agricultural studies (Lacoste et al., 2017). Borrowing from ethnography, varied notes and observations about the land and the people were accumulated, not only during the first two steps of the diagnostic but throughout the entire procedure (Cochet, 2015; Aubron et al., 2016; Lacoste et al., 2016). In many instances, side topics would thus be investigated, non-agricultural activities enquired about, and deviations from a given line of questioning pursued. Exploration was not always fruitful but sometimes led to the discovery of unexpectedly important aspects (for instance here, the importance of generation ratios). Furthermore, the large amounts of background information gathered on both technical and social aspects permitted to cross-check the quantitative data to ensure its quality,
and to contribute to the prioritisation process (level of detail and hierarchy of criteria). Notably, the physical exploration of the study area permitted to determine relevant stratifications for the purposive sampling (landscape zones, then farming systems). Another advantage of explorative methods is to develop trust between the investigator and the local population, fostered by the necessity to reside at least partly in the study area.

Thirdly, the purposive sampling technique that combined stratification, theoretical saturation and cold calling ensured the sample was representative. Sampling biases were also considerably reduced by achieving a near 100% response rate (no self-selection or under-coverage), and by avoiding existing farm listings (no over-reliance on key resources people who can develop routine answers). Including all types of farms was crucial for the study, since the objective was to identify farming systems, not to provide averages based on a random sample. The typology could thus include farming businesses whose managers stated they were never or very rarely surveyed. This was shown with the smallest farms being seldom surveyed but proving essential to determine the boundaries to the ranges of existence for the “standard” farming systems. The reasons identified included being too small, too rare, difficult to access, not registered as clients in consultant and commercial databases, and not listed as potential partners by government and institutions due to lack of resources, or simply, community presence. By contrast, the rare “huge” farms were involved in multiple social activities and research projects, regularly providing farm information, notably as case study farms. This study showed that this often pro-active participation does not, however, provide representative or even average practices for the region, a pitfall also noted by Navarro et al. (2016).

Fourthly, one-on-one in-depth semi-structured interviews were an indispensable tool, providing a platform for exploration by stimulating discussion free of peer-pressure, and limiting response biases by allowing respondents to take their time and contextualise their responses, adjusting questions if relevant (Roulston, 2010; Barral et al., 2012). Providing time and room for explanations also limited “box-ticking” behaviour as well as circumstantial numbers (e.g. data reflecting extra-ordinary years rather than the representative situation on which the agronomic logic of the system is built), allowing to better determine what would constitute the typical value upon which the characteristics of typical farming systems are based. Collecting extra information is particularly useful for variables with high degrees of variability and uncertainty (e.g. grain yields in Mediterranean environments), or that are inherently difficult to quantify (e.g. management strategies). Taking into account a high number of related facts permits the triangulation of representative values with a higher probability of accuracy.
than, for instance, simply averaging recent longitudinal records from accounting books. In fact, by purposively avoiding this source of information, the agrarian diagnostic confidently captured actual practices while eluding partial records, measure errors, and discrepancies arising from the variability of seasonal and operational conditions (Navarro et al., 2016). Importantly, response biases were also managed by the type of questions asked, that favoured “how” and oriented “why” toward the characterisation of situations. As argued by Katz (2001, 2002), this directed interviews toward causal explanations anchored in pragmatic facts, rather than eliciting discourses likely to include a range of biases (notably determinism and cognitive biases to rationalise paradoxes, or anticipation of what an appropriate response might be for the investigator’ audience).

Lastly, it should be highlighted that the use of qualitative techniques does not entail a full participatory process which, although essential, only regards the final step of the diagnosis. In fact, the importance of an external expertise is emphasised to avoid cognitive biases: the investigator must not be a local resident, and respondents are not involved in the analytic process. In addition, attitudinal variables are not included. On the other hand, the multi-functionality of agriculture is part of the framework (activity system level, not used here but always considered). Consequently, the typologies produced in comparative agriculture do not align with the qualitative, participatory approaches that are classically opposed to quantitative, statistical procedures (Aouadi et al., 2015; Kuivanen et al., 2016b). The methods of comparative agriculture do not represent a middle ground between the qualitative and quantitative approaches, but a complementary alternative that integrates specifics strengths from both sides to achieve its own objectives.

4.3 Conceptual originality: achieving integration by departing from individuals assessments

Last but not least, the theoretical framework used in comparative agriculture also contributed to constructing an effective farming system typology. Specifically, the original concept of the agrarian system added to the analytic choices and methodological tools described above by conceptualising farming systems through groups of farms rather than individual situations.

The agrarian system represents agricultural situations as composed of a limited number of farming systems. The premise is that internal and external pressures on production processes only permit a certain number of them to co-exist, a theory showing similarities with those encountered in evolutionary economic geography (Boschma & Martin, 2010). Individual situations all vary to some extent, but a limited number of sub-populations can be identified within which farmers share relatively
similar resources and constraints, and whose interest is to implement systems that are thus relatively similar (the validity of this framework was confirmed here for the study area, with the vast majority of farms distributed between only four farming systems that comprised a total of five sub-systems; one of them, on sandy soils, common to all). The variation encountered is thus simplified into a limited number of farming system models which permits to build the typology by comparing farms across a wide range of variables concurrently (empirical analytic process). Each group of farms is assessed as a whole to identify what constitute its “heart”, i.e. its specificities in terms of structure and functioning, which are used to define the farming system. Then, using information from the entire group permits to populate the components of that farming system quickly, effectively bypassing the need for longitudinal information across several farms and years. Efficiency is demonstrated by the small sample size necessary to draft the typology (a dozen farm businesses, i.e. <20% of the farm population; the final sample comprised 50% to cater for the double requirements of characterising farming systems in details and of conducting statistical analysis).

Naturally, the agrarian system presents many similarities with principles used in modern farming system research since the concept, like the methods of the agrarian diagnosis, results from adapting inputs from a range of disciplines (Cochet, 2012, 2015). Similarities notably exist with the approaches taken by Tittonell et al. (2005), Girard et al. (2008), Choisis et al. (2012), and Blanchard et al. (2013) to assess farming diversity. However, the departure from individual-based approaches strongly sets comparative agriculture and its outputs apart. In essence, the process permits to link complex systemic theory with empirical regional data while achieving the high degree of spatial, temporal and topical integration that is necessary to a holistic investigation. Both aspects are rarely achieved concurrently, in spite of their importance to characterise the variability of agricultural systems (Surendran Nair et al., 2016).

For instance, modelling farming systems using sub-systems and components that interact with varied degrees of complexity, complementarity and competition, at varied temporal and spatial scales, is not unique to the agrarian system concept. However, farming system studies that examine agronomy processes normally focus on the plot, or the plot and farm, more rarely integrating regional scales and human aspects as well (Asseng et al., 2010). In comparative agriculture, modelling agronomic processes based on a groups of farms permits to include all scales, integrating complementary angles that may otherwise be missed. In this study, soil and rotation data was compared to the agrarian system template before attempting analysis with individual data. For each farming system, farms as a group provided a critical mass of information permitting to consider landscape, farm and plot scales concurrently,
through both yearly and long-term lenses. This permitted to identify co-existing cultural sub-systems not noticeable when only considering whole-farm enterprise mixes, or too variable to segregate effectively when recording plot-specific history.

The agrarian system also permits to integrate technical and social aspects. The concept thus joins the abundance of theories and approaches in modern farming system research that recognise the necessity to pinpoint the rationale of production systems as well as the importance, to do so and to induce change effectively, of including human-related factors (van der Ploeg et al., 2009; Tittonell et al., 2010; Darnhofer et al., 2012). This implies recognising the non-static nature of farming systems and the importance of economic, institutional and political relationships, as do for instance the disciplines of political ecology or environmental history (Cochet, 2012; Fischer-Kowalski et al., 2014; Gautier & Hautdidier, 2015; Gautier & Kull, 2015). The concept of agrarian system thus shows strong similarities with social-ecological framings that are increasingly used in agricultural studies. However, beyond integrating theories and standard variables, applied studies that effectively integrate detailed technical and social aspects to explain the organisation of farming systems at the farm, plot and landscape levels are lacking (including in Australian farming system research, Lacoste et al. (2017). Studies that do may investigate the interaction of these mechanisms in great detail but use case studies for validation and recognise extrapolation difficulties (e.g. House et al., 2008; Rodriguez et al., 2011; Kalaugher et al., 2013). Here, results relevant from both an agronomic and a socio-economic perspectives were produced for an entire region, linking the conditions for the presence of given mechanisms to detailed human-related aspects (e.g. animal sub-systems and grain post-production strategies with the availability of specific types of workforce). This was done cost-effectively, with the entire data collection and analysis conducted by one investigator during a few months (or less, if no additional data had to be collected for the extended purposes of this study). In contrast, standard statistical procedures typically rely on large databases (agricultural census and surveys) which collection involved the deployment of national agencies resources or state-wide private companies for usually low levels of details, or, when data is not already available, several hundred paper or phone surveys which completion, transcription, cleaning and analysis may involve several researchers over a similar or longer duration. The methods of the agrarian diagnosis provide an overall less costly, more detailed, and more effective alternative suited to all situations, including data-poor regions.
5. Conclusions

The objective of this study was to demonstrate the value of comparative agriculture in determining regional diversity in terms of farming systems, i.e. using both structural and functional aspects that holistically reflected the resources, production and organisation of the entire farm. This was done successfully in a broadacre situation, for which analogous efforts are lacking. A typology was determined comprising farming systems that differed across numerous variables, in spite of agriculture in the region being little diversified. Importantly, the procedure used is replicable and did not rely on local expert knowledge.

The tools of comparative agriculture thus proved successful in solving the analytical and practical challenges faced by applied studies which goals are holistic. This was done using multi-disciplinary concepts and mixed methods, which are approaches increasingly recommended to solve complex problems. The investigation thus considered and integrated a wide range of farming systems aspects while remaining manageable and actively reducing a range of biases. Quality information that was detailed, varied and representative of the range of situations present in the study area was collected in sufficient amounts to carry out a well-informed analysis, as well as confirmatory statistical tests. By identifying criteria progressively and empirically, the methods employed were more effective for the holistic objectives of this study than choosing criteria first then applying the multivariate clustering procedures commonly employed to investigate farming diversity. The results of this study thus suggest that the discipline of comparative agriculture is able to make important contributions to modern farming system research and deserves wider application.

Acknowledgments

This work was funded by the Australian Government, Department of Education (IPRS/APA scholarship), and by the Grains Research and Development Corporation of Australia (GRDC, GRS scholarship). The authors also thank two anonymous reviewers for their constructive comments, Stephen Powles for his continued support, as well as Shauna Wells, Chris Syme, Dennis and Glenda Pease for valued field support. The authors would also like to sincerely thank all the farmers who contributed their time to this study, and the town of Wyalkatchem for the constructive cooperation of its residents.
References


DAFWA. (2014). Evolution of drought policy in Western Australia. Perth: Rural Business Development Unit, Department of Agriculture and Food Western Australia (DAFWA).


in vulnerable areas. *Agriculture, Ecosystems & Environment*, 147, 89-99. doi:10.1016/j.agee.2011.06.005


118


CHAPTER 4

Further methodological capabilities of comparative agriculture:

Linking farming resources, practices and performances

(article, PDF)

This section reproduces the PDF of the article accepted for publication in Agriculture, Ecosystems and Environment on the 19th of September 2016.

1. Abstract & Introduction: Lacking information on resources & practices 123
2. Material & methods: Landscape analysis & farmer interviews 125
3. Results: Distinct production practices captured & quantified 128
4. Discussion: New insights about complex farming system relationships 130
5. Conclusions, Acknowledgments, References 135
Comparative agriculture methods capture distinct production practices across a broadacre Australian landscape

Myrtille Lacoste\textsuperscript{a,b}, Roger Lawes\textsuperscript{a}, Olivier Ducourtieux\textsuperscript{c}, Ken Flower\textsuperscript{a}

\textsuperscript{a} University of Western Australia, School of Plant Biology, Crawley, WA 6009, Australia
\textsuperscript{b} CSIRO Ecosystems Environment, Floreat, WA 6014, Australia
\textsuperscript{c} AgroParisTech, UMR Comparative Agriculture, UMR PROINC 75231, Paris Cedex 05, France

\section*{ARTICLE INFO}

Article history:
Received 25 February 2016
Received in revised form 3 September 2016
Accepted 19 September 2016
Available online xxx

Keywords:
Soil heterogeneity
Land use
Rotation
Sequence
Farmer
Mixed methods

\section*{ABSTRACT}

In farming systems research the link between farm resources, management and performances is often described, but rarely confirmed or quantified. Problems arise in formalising such linkages because substantial spatial and longitudinal whole-farm data are difficult to acquire. This study used the integrative discipline of comparative agriculture to collect such information and address a wide range of related farming system questions. The mixed method procedure included a landscape analysis, a historical investigation, and the collection of current farm information from 36 farms, representing half the farming businesses of a 4 000 km\textsuperscript{2} area in a region of the Western Australian wheatbelt (=300 mm/year) with highly variable soils.

Land types influence management, including cropping specialisation, and explained some of the regional variability in grain yield and enterprise mix. Rotations varied by soil type and farm type. On average their duration was 3--4 years, typically starting with a 2--3 years of wheat, resulting in overall composition of 64% cereals, 20% break crops and 16% pastures/fallow. Break crops were grown more often on light sandy soils than on heavier fine-textured soils. Lights soils were managed similarly by all farmers but distinctions occurred on heavier soils between mixed crop-livestock farmers and cropping specialists. This divergence in farming production was explained by soil composition; whilst cropping appears more profitable in the region, mixed farmers retained animals and pastures as a strategy to cope with having greater proportions of land less suited to crop production. Typical farm grain yields were indeed found to vary in relation to farm soil composition. The location of the original family farm in the landscape is likely to explain these differences in farm land resources, and subsequently current farm performance, production strategies and trajectories.

This study highlighted the potential of a method that deserves wider application: comparative agriculture helped identify and establish complex relationships within the farming system, some of which challenge common assumptions. Further applications to define typical farms, monitor practices, and contribute meaningful divisions of agriculture landscapes are also discussed.

\textsuperscript{c} 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

\section*{1. Introduction}

The importance of soil type on agronomic performance is widely recognised, however the impacts of soil variability at the farm level are more difficult to assess. In farming system research, assumptions are commonly made about farming practices that are not validated, prompting questions as to what extent the farmers’ objectives and the criteria that influence their management are integrated. In particular, farmers are known to manage soils differently, however the impact of soil heterogeneity on their practices is rarely quantified.

In low rainfall southern Australia, where winter cereals and mixed crop-livestock farming systems dominate, controlled experiments, field surveys and simulation modelling thus regularly demonstrate that soil types have a major influence on crop production and resource use efficiency. Effects may be further amplified by variations in rainfall amount and distribution (Lawes et al., 2009; Oliver et al., 2009; Seymour et al., 2012; Harries et al., 2015; McBeath et al., 2015). At the field level, optimal production performances may be achieved by matching management to soil type, particularly with regards to crop and pasture rotations as it

\url{http://dx.doi.org/10.1016/j.agee.2016.09.020} 0167-8809\textsuperscript{c} 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
has historically been the case in other Mediterranean environments (Mazoyer and Roudart, 2007). Broadacre practicalities may lead to simplifications, for instance choosing practices that fit the dominant soil type. At the farm level, further compromises may be necessary as farmers must ensure the economic and biophysical sustainability of very large farms, and must also consider external factors (Bell and Moore, 2012; Price and Leviston, 2014).

There have been, however, few attempts at describing the rotations these broadacre farmers actually implement across different soils types. At present, the main maps available at regional scales include crop capability and soil/landscape surveys (e.g. van Gool et al., 2008; Sawkins, 2010), but none show how the rotation strategies of farmers differ across the landscape. Partial surveys recording the crop and pasture history of fields are regularly conducted (e.g. in Western Australia Lawes, 2010; Harries et al., 2015), however these do not provide a farm-scale picture of how landscape heterogeneity influences the rotation strategies of farmers. Whilst regional, averaged rotations might be deduced from overall land use (e.g. Robertson et al., 2010), the management patterns of farmers across different soils are not characterised or quantified. For instance, it is not known whether and to which extent rotations do vary between soils and farmers, or how the farm soil composition impacts the farm enterprise mix and overall performance. Although sometimes hypothesised, it is thus unclear whether the move from mixed crop-livestock farming to specialised crop production is prompted by particular soil types on farm and whether this decision to re-orientate production leads to higher grain yields overall. In fact, the amount of observed variability in individual performances that can be attributed to differences in farm soil composition is yet to be determined.

Whole farm surveys that could answer these types of question are not conducted for practical reasons. The long-term and spatial nature of rotation information implies that recording detailed and complete data about all the crop and pasture sequences implemented by farmers represents an unmanageable task. Case studies are detailed, but low numbers and/or focus on given fields hinder extrapolation (e.g. House et al., 2008; van Rees et al., 2014). Studies investigating variations in regional farm performances can thus seldom account for the variability of farm soil resources in spite of acknowledging its importance, let alone compare longitudinal data describing the utilisation of the landscape, even when farm surveys are available (Hooper et al., 2011; Hughes et al., 2011; Lawes and Kingswell, 2012; Kingswell et al., 2013).

In contrast, a large body of modelling literature has been produced that investigates farm soil profiles, rotations and performances at various spatial and temporal scales, notably using the APSIM, APSFARM, MIDAS and LUSO models (e.g. Moore et al., 2011; Finlayson et al., 2012; Kragt et al., 2012; Rodríguez et al., 2014; Lawes and Renton, 2015). Promising avenues to integrate social behaviour and landscape heterogeneity are also investigated (e.g. agent-based models, Asseng et al., 2010). The objectives of these modelling studies are generally to evaluate the impacts of adopting new technologies, practices, plant species or policies on farm management and performances. This is typically achieved by determining the allocation of farm resources that optimises farm production, financial return, or a desirable soil characteristic (e.g. organic carbon), under varying farm profiles (e.g. soil composition) and scenarios (e.g. changing prices or climate). Solutions notably reside in adjusting the farm enterprise mix and rotation strategies. The research questions and assumptions about farms in a region, for which these studies are based upon, are usually derived from case studies, local expert opinion and national surveys. More details on the practices that dominate different areas of the agricultural landscape could improve baseline information and contribute to model validation.

This study employed a novel, applied approach to examine the impact of soil heterogeneity on farmers’ practices, production orientation and crop performances, expressed as rotation composition, farm type and grain yield, for a region of the Western Australian wheatbelt with high soil variability (Sawkins, 2010;
Schoknecht and Pathan, 2013). The procedures used are those of comparative agriculture, a discipline which emphasises landscape analysis (Barral et al., 2012; Cochet, 2012; Moreau et al., 2012; Aubron et al., 2016) and which no equivalent has been used to study Australian agricultural systems before (Lacoste et al., in press). Both qualitative and quantitative perspectives are employed to cost-effectively collect spatial and long-term farming information, with exploratory landscape and historical investigations preceding farmer interviews. Notably, a multi-scale zonal approach is combined to detailed assessments, which as suggested by House et al. (2008), can solve extrapolation problems when faced with land and management variability issues. These mixed methods and their open data collection process are presented, before discussing how the results contribute to current farming practice knowledge in Western Australia. Wider implications of using comparative agriculture tools for the study of broadacre farming systems are also highlighted.

2. Material and methods

2.1. Region

The study area was located in the Western Australian wheatbelt, one of Australia’s main grain growing regions. Ten million tons of grains are produced across this 20 million hectare region by about 4000 rainfed broadacre farms. This includes a third of the country’s wheat tonnage, produced with yields slightly less than 2t/ha on average (AABARES, 2014). The study area occupies approximately 4000 km² and is bounded by the towns of Cunderdin, Kellerberrin, Wyalkatchem and Trayning (117°28’E, 31°23’S, Fig. 1). The area was chosen for its central position in the wheatbelt, for its relevance to the wider Mortlock sub-region (Calloway, 2004), and for the ongoing focus of local research efforts allowing for comparisons and further use of results. Boundaries were set to include a wide range of landscape variations (Sawkins, 2010). Although the study area is dominated by sands, soil heterogeneity is high due to layered lateritic profiles that are eroded to varied extents and further complicated by biogenesis (Verboom and Pate, 2013).

The climate is Mediterranean-type, with hot dry summers and cool wet winters. Annual rainfall is low and variable, on average 300 mm for the last 15 years but with highest and lowest quartile years averaging 360 and 220 mm respectively. About 65% of the annual rainfall occurs during the growing season between May, when annual crops are generally sown, and October (BOM, 2015). Crops are harvested in November and December.

Since European settlement in the 1900s, farms in the region have implemented a combination of livestock enterprises dominated by sheep for wool and cropping enterprises dominated by winter cereals. Since the 1960s, other enterprises include legumes (clover-dominated pastures, lupins, peas), meat, and more recently oilseeds (canola). Livestock numbers and legume pastures have been in decline since the early 1970s, mirroring trends in the rest of the Australian cereal-sheep zone (Bell and Moore, 2012). The majority of farm businesses are now crop dominant and use no-till seeding systems, with sheep mostly grazing annual volunteer pastures and crop stubbles (Fisher et al., 2010; Thompson, 2015).

2.2. Procedure and data

Data was collected over 12 weeks by one investigator during May-August 2014. As outlined in Fig. 2, the mixed methods procedure included a landscape analysis, an historical investigation and the characterisation of current farming systems. The first two steps facilitated the definition of spatial units and interview guidelines for the third step. The principles followed were those of a procedure named an “agrarian system diagnosis” which is central to the discipline of comparative agriculture (Barral et al., 2012; Moreau et al., 2012; Cochet, 2015; Aubron et al., 2016). Three aspects were specifically used in this study. First was to rely primarily on information sourced first-hand, through direct observations and interviews. Second was to integrate multi-disciplinary aspects, notably by collecting both quantitative and qualitative information on a variety of topics. Third was to

![Fig. 2. Data collection procedure (agrarian system diagnosis). Respondents are identified while scouting the study area, using maps and snow-balling. Selection is random stratified within landscape zones, recruitment is by cold-calling. Interviews are semi-structured and in-depth. Interview duration and respondent numbers are determined by saturation, i.e. after no new information arises, only repetitions, which depends on the number and complexity of local farming systems.](image-url)
iteratively prioritise the information to collect, each step of the procedure informing the next. Part of this included the identification of agro-ecosystems at different scales, which here were best termed as “landscape zones” and “broad soil types”.

2.2.1. Landscape analysis

The first step of the procedure consisted of drafting relatively homogenous landscape zones in the study area using published material and field observations (Fig. 2.1, Table 1a). Information was first inferred from satellite imagery and existing maps, then compared with direct observations made over 3 weeks travelling by car in the study area across potentially interesting transects. This led to the identification and mapping of 5 initial landscape zones which largely overlapped the existing WA “landscape system” mapping (Sawkins, 2010). The latter was not directly used because of the requirement to obtain farmers’ insights that are not usually captured. Additional outcomes included familiarisation with the study area and the identification of local contacts.

2.2.2. Historical investigation

The second step used historical information (Fig. 2.2, Table 1b), mainly sourced from retired farmers across 4 weeks of interviews, to (i) improve and validate the draft landscape zoning by appraising the localisation of land use changes, and (ii) to prepare interview guidelines with current farmers by appraising when and how land use and farming techniques diverged in the recent history to lead to current farming systems. Local archives and historical accounts from public libraries were used as well when possible.

Interviews were in-depth and semi-structured, following a pattern of questions but leaving responses open-ended to stimulate discussion. Questions started with general farm characteristics (location, soils, rainfall, areas) and continued onto the farm history following a chronological order. Questions included: origin of farm and capital; farming start, family structure, siblings roles; changes in farm area, workforce, equipment, production orientation, practices; retirement and current farm situation, children’s occupation; notable events; introduction and adoption of memorable technologies, techniques, goods and services; changes in production levels. Emphasis was placed on dating and locating changes, specifically asking where management practices and productions differed, in the different parts of the farm and in the broader landscape (e.g. different fields clearing dates, input levels, enterprises, machinery requirements, etc.). Respondents were recruited directly door-to-door (cold calling), after being identified from previous participants (snowballing) or while driving in the study area during the first phase of the analysis (scouting). At first, respondents were selected at random within each landscape zone. Then, a purposive sampling technique was applied in order to represent all landscape zones. Interviews were always conducted face-to-face, and mostly one-on-one to avoid group bias and ensure confidentiality. Interviews were conducted until no new information arose (i.e. saturation). This occurred after 17 interviews involving 22 respondents (response rate: 96%), each lasting 1.5 h on average (notes taken, no transcribed recordings).

The addition of historical criteria (Table 1b) led to combine landscape parts that were distinct geographically but overall similar, finally resulting in 3 main landscape zones termed “undulating sandplains”, “hilly sandplains” and “valley floors”. Their main distinctive features are listed in Table 2, completed by Fig. 3.

In their interviews, retired farmers contrasted 6 broad arable types on the basis of physical properties, distinctive native vegetation, production levels and management requirements. This information and local knowledge collected about the study area were used to build interview guidelines and determine questions for the next step of the procedure.

2.2.3. Characterisation of current farming systems

The third step (Fig. 2.3) consisted of collecting detailed information from current farmers to characterize more precisely the different farming systems and practices identified during the historical investigation (4 weeks). Active farmers generally identified the same 6 broad arable types as retired farmers. However, some of these soils covered very small areas or were managed similarly, despite their heterogeneity. Consequently, 3 main soil types simply labelled “light”, “medium” and “heavy” were finally retained as spatial units for analysis (Table 3).

Interviews were also semi-structured and in-depth, but followed a more focused pattern than those of retired farmers (Table 4). Not all questions could be asked to all respondents, depending on their available time. Most of the quantitative data collected was enriched with qualitative information such as

<p>| Table 1 |
| Criteria initially considered to contrast homogenous landscape zones. |</p>
<table>
<thead>
<tr>
<th>Type</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a. Landscape analysis (existing material and field observations)</strong></td>
<td></td>
</tr>
<tr>
<td>Morphology</td>
<td>Elevation, relief, overall landscape shape (e.g. hills, plains, ridges, rocky outcrops)</td>
</tr>
<tr>
<td>Geology</td>
<td>Base rocks, mines</td>
</tr>
<tr>
<td>Pedology</td>
<td>Soils</td>
</tr>
<tr>
<td>Hydrology</td>
<td>Rivers, creeks, ponds, aquifers, water flows and regimes</td>
</tr>
<tr>
<td>Vegetation</td>
<td>Land cover, native and introduced species, micro-climates</td>
</tr>
<tr>
<td>Land use</td>
<td>Crops, pastures, plantations, reserves, shape and size of fields, seasonal agricultural activities</td>
</tr>
<tr>
<td>Housing</td>
<td>Location and nature (e.g. grouped, dispersed, abandoned)</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Transport network, buildings (e.g. storage), power and water supply, dams</td>
</tr>
<tr>
<td>Administrative divisions</td>
<td>Local government boundaries, cadastral plans</td>
</tr>
</tbody>
</table>

Notable published sources relevant for this study included: a) Geoscience Australia, 1970a,b,c; Mulhling and Thom (1985); Lefroy et al. (1991); Lantzké and Fulton (1992); McArthur (1992); Lantzké and Fulton (1993); Greetham and Wagner (1995); Verboom and Paz (2003); Byrne (2005); Sawkins (2005); Schokker and Pathan (2013); Verboom and Paz (2013); Duncon (2014); Google (2014). b) Appleyard and Cooper (2009); Coles (1969); Lindsay (1997); Rance (2000).
Table 2
Landscape zones identified in the study area using published material, direct landscape observations and interviews with retired farmers.

<table>
<thead>
<tr>
<th>Final landscape zones</th>
<th>Undulating sandplains</th>
<th>Hilly sandplains</th>
<th>Valley floors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial 5 zones drafted (and corresponding WA landscape systems)</td>
<td>°North-East sandplains&quot; (Tangredin)</td>
<td>°North-West sandplains&quot; (Kwoylin)</td>
<td>°&quot;Valleys&quot; (Kellerberrin and Wallambin)</td>
</tr>
<tr>
<td>Elevation (a.s.l.)</td>
<td>250–300 m</td>
<td>250–350 m</td>
<td>200–250 m</td>
</tr>
<tr>
<td>Morphology (see Fig. 3)</td>
<td>Undulating, open country</td>
<td>Generally steeper, more frequent vegetation, rocky outcrops and gravely corts</td>
<td>Generally flat, salt lake system and tributaries secondary beds</td>
</tr>
<tr>
<td>Dominant geology (see Fig. 3)</td>
<td>Colluvium, laterite, granitic rocks</td>
<td>More granitic</td>
<td>Alluvium</td>
</tr>
<tr>
<td>Land use</td>
<td>Crops</td>
<td>Crops, more pastures, rocky reserves</td>
<td>Crops, more pastures, saline reserves</td>
</tr>
<tr>
<td>Cadastral pattern</td>
<td>Regular, large fields</td>
<td>Varied, mostly smaller and irregular</td>
<td>Varied, mostly smaller and irregular</td>
</tr>
<tr>
<td>Road network pattern</td>
<td>Secondary, regular grids</td>
<td>Secondary, irregular</td>
<td>Primary, Major townships,</td>
</tr>
<tr>
<td>Historical highlights</td>
<td>Bushes</td>
<td>Varied</td>
<td>Large trees and mallee formations</td>
</tr>
<tr>
<td></td>
<td>Second clearing phase (1960s), value increase after production increases with ameliorants (1970s), no townships</td>
<td>Second railway, Early developments (rock water pools)</td>
<td>First settlements (1980s), developments (clearings, fencing, water), transport incl. first railway</td>
</tr>
</tbody>
</table>

Fig. 3. Landscape zones identified in the study area.
Boundaries, schematic cross-sections with dominant morphology and geology, typical features.
Table 3
Major arable soil types identified in the study area during interviews with retired and active farmers.

<table>
<thead>
<tr>
<th>Final soil types</th>
<th>Light</th>
<th>Medium</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial 6 soil types, local names</td>
<td><em>Tanna country</em></td>
<td><em>Mixed medium soils</em></td>
<td><em>Limber/gimlet/salmon gum loams</em></td>
</tr>
<tr>
<td></td>
<td><em>Woolgoolga sands</em> (small areas)</td>
<td><em>Jam country</em> (both managed similarly)</td>
<td><em>Blue/grey/red clays</em> (small areas)</td>
</tr>
<tr>
<td>WA soil types</td>
<td>Deep sands, gravelly sands, sand over loams or gravels (duplexes)</td>
<td>Similar to light soils with more shallow loams and sands, and more rocks</td>
<td>Loams, loamy clays and sands, clays, saline, sodic and waterlogged areas</td>
</tr>
<tr>
<td>WA soil landscape unit classification</td>
<td>Ulva, Boosaan</td>
<td>Doncaster, Collar</td>
<td>Belka, Ningeenan, Bannede</td>
</tr>
<tr>
<td>Australian soil classification</td>
<td>Chromosols, kandosols, sodosols</td>
<td>Sodosols, chromosols, kandosols, demosols, sodosols</td>
<td>Sodosols, vertosols, demosols, hydrosols</td>
</tr>
<tr>
<td>Distinctive vegetation</td>
<td>Black tama (Allocasuarina arizatii), wodjil (Acacia neumphyli)</td>
<td>Rock sheoak (Allocasuarina huegeriana), jam wattle (Acacia aruncate)</td>
<td>Salmon gum (Acacia prua salomonophia), gimlet (E. salubris), samphire (Halosorus spp.)</td>
</tr>
<tr>
<td>Relative production levels</td>
<td>Typically higher for lupin, clover, wheat (except on wodjil sands)</td>
<td></td>
<td>Barley better than wheat in sodic soils</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Highest cereal yield potential in wet years</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>More frequent following, early seeding, difficult land preparation</td>
</tr>
<tr>
<td>Major management differences</td>
<td>More fertiliser, often phosphate deficient, wet seeding (erosion risk)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* This nomenclature is relative and to be understood in the Western Australian context where sands dominate: most local “heavy” soils may not be as fine-textured as in other locations (including for instance more loamy sands than clays).

background events, constraints, anecdotes, personal experience, expected goals, etc. This allowed cross-checking values and assessing ranges, particularly for variables integrating long-term dimensions such as yields or field operations. In these cases, particular care was taken to obtain typical values representative of the most common range of situations encountered by farmers.

The identification, selection and recruitment process of respondents was identical to that of retired farmers. Saturation occurred after a dozen interviews, however additional respondents were sought to ensure the statistical significance of the quantitative results. A total of 35 interviews (response rate: 97%, duration: half an hour to 3h) were thus conducted with 39 respondents representing 34 farming businesses. Only one was discarded due to incomplete data, whilst information sourced from 3 retired farmers whose business was still active could be added, bringing the sample to a total of 36 farms. Based on local knowledge and maps, this represented about half the farms of the study area. Average farm area in the sample was 5 000 ha, ranging from 780 ha to 16 500 ha (90% between 1 300–10 000 ha), 90% of which was considered arable. 56% were mixed crop/sheep farmers and 44% were cropping specialists who did not raise livestock or implement pastures on arable land.

2.3. Statistical analysis

Statistical analysis was performed on the variables listed in Table 4 using R (R Core Team, 2015).

Differences in soil type areas, yields and other farm characteristics were tested across categorical variables (farm type and landscape zone) using non-parametric Wilcoxon-Mann-Whitney tests on medians (one-way, set during the explorative phases of the analysis).

Linear models were used to fit a range of dependent and explanatory variables to farm soils and farm grain yields. For example, models tested whether overall farm management and production aspects such as typical seeding start dates, fertiliser use and farm yields were explained by the importance of a given soil within the farm. Mirror models tested for instance whether the occurrence of a soil type could be explained by farm and farm manager characteristics such as farm size, arable area, or professional advice received. The terms from Table 4 were systematically added and removed from the models to determine whether their inclusion improved model performance using both backward and forward stepwise selection based on Akaike Information Criteria. Model residuals were checked for outliers and violations of assumptions. After the best explanatory variables fitted as main effects were identified, correlations were checked to avoid redundancy and over-fitting, and interactions were tested. Final model selection was evaluated using ANOVAs. From these, partial models were produced by fitting individual terms against the raw data, in order to assess their individual contribution to the explanation of variance. Linear mixed effects models with farms fitted as random effects were conducted to test the impact of soil type on the duration and composition of rotations (NLME, Pinheiro et al., 2015). The relevance of including the terms from Table 4 was tested following the same procedure described above.

3. Results

3.1. Impact of landscape zones on farm soils

All three arable soils types (light, medium and heavy) were present on farms located in each of the three landscape zones (undulating sandplains, hilly sandplains, valley floors); however, proportions differed (Fig. 4). The occurrence of two other soil characteristics also varied, namely arable rocky soils and non-arable soils. Farms located on valley floors featured the least amount of light soils and the most of heavy soils and non-arable land, the latter generally corresponding to saline areas. Farms located on the two sandplains zones had similar proportions of light and medium soils but differed in terms of heavy soils and rocky soils, more of which was found in the hilly sandplains.

3.2. Impact of soils on crop performances and production orientation: farm yields and farm types

The managers of all 36 farming businesses characterised soils primarily on the basis of physical properties, even when their own farm featured only one major soil type (only 4 cases). However, distinctions in terms of crop production levels were not always made. Only 40% of 32 respondents mentioned that light soils were more reliable than heavy soils, having generally produced better grain yields in the dry conditions that had dominated the past decade, even when difficult rainfall patterns occurred (e.g. late first rains). Seven respondents provided typical yields for both light and
Table 4
Progression of semi-structured interviews with current farmers: topics covered and variables collected that were included in statistical analysis.

<table>
<thead>
<tr>
<th>Questions asked and corresponding variables</th>
<th>Unit(s)</th>
<th>Number of observations</th>
<th>Inclusion in statistical analysis:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Land</td>
<td></td>
<td></td>
<td>Tests in median</td>
</tr>
<tr>
<td>Farm location (3 landscape zones)</td>
<td>n.a.</td>
<td>34</td>
<td>EF₁</td>
</tr>
<tr>
<td>Typical annual rainfall</td>
<td>mm</td>
<td>27</td>
<td>E</td>
</tr>
<tr>
<td>Farm area</td>
<td>ha</td>
<td>36</td>
<td>E</td>
</tr>
<tr>
<td>Non-arable area</td>
<td>ha</td>
<td>36</td>
<td>one-way</td>
</tr>
<tr>
<td>Arable areas typically under wheat, barley,</td>
<td>ha</td>
<td>36</td>
<td>E</td>
</tr>
<tr>
<td>canola, legume crops, fallow, volunteer</td>
<td></td>
<td></td>
<td>E/D</td>
</tr>
<tr>
<td>pastures, legume pasture and permanent</td>
<td></td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>pasture (not rotated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farm production orientation (2 farm types)</td>
<td>n.a.</td>
<td>36</td>
<td>EF₂</td>
</tr>
<tr>
<td>Rocky arable area</td>
<td>ha</td>
<td>35</td>
<td>EF₂</td>
</tr>
<tr>
<td>Soil types present on farm (3 major soil</td>
<td>n.a.</td>
<td>36</td>
<td>EF₁</td>
</tr>
<tr>
<td>types)</td>
<td></td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Soil types, proportion of farm arable area</td>
<td>%</td>
<td>35</td>
<td>one-way</td>
</tr>
<tr>
<td>Typical rotation on each soil type(1,2)</td>
<td>n.a.</td>
<td>83 (33 farms)</td>
<td></td>
</tr>
<tr>
<td>Seeding priority criteria</td>
<td>n.a.</td>
<td>23</td>
<td>E</td>
</tr>
<tr>
<td>Other management differences between soil</td>
<td>n.a.</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>types</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Grain yields</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical farm grain yields (wheat, barley,</td>
<td>t/ha</td>
<td>31, 17, 16, 15</td>
<td>one-way</td>
</tr>
<tr>
<td>canola, lupin)</td>
<td></td>
<td></td>
<td>D</td>
</tr>
<tr>
<td>Differences in typical wheat yield across</td>
<td>t/ha</td>
<td>32</td>
<td>one-way</td>
</tr>
<tr>
<td>soil types</td>
<td></td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Typical high and low farm wheat yields</td>
<td>t/ha</td>
<td>22</td>
<td>one-way</td>
</tr>
<tr>
<td>Other performance differences between soil</td>
<td>n.a.</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>types</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farm history</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date current manager started farming</td>
<td>date</td>
<td>36</td>
<td>E</td>
</tr>
<tr>
<td>6. Workforce(5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permanent labour, family and employed</td>
<td>FTE</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Casual labour employed at seeding</td>
<td>FTE</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>7. Calendar of operations(6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start of seeding</td>
<td>date</td>
<td>33</td>
<td>E/D</td>
</tr>
<tr>
<td>End of seeding</td>
<td>date</td>
<td>33</td>
<td>E/D</td>
</tr>
<tr>
<td>8. Machinery and buildings(7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration of seeding shift</td>
<td>hours</td>
<td>30</td>
<td>E</td>
</tr>
<tr>
<td>9. Inputs and expenses(9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat fertilisers (P total, N total, upfront,</td>
<td>units/ha</td>
<td>26, 28, 25, 24</td>
<td></td>
</tr>
<tr>
<td>top-up)</td>
<td></td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Consultants (agronomists and farm advisors)</td>
<td>k$/paid/yr</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>10. Banking, challenges and plans(9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equity level</td>
<td>ranked 1-5</td>
<td>28</td>
<td>E/D</td>
</tr>
<tr>
<td>Calculated variables derived from above data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotation duration(9)</td>
<td>year</td>
<td>83</td>
<td>D</td>
</tr>
<tr>
<td>Rotation composition(9) in wheat, barley,</td>
<td>%</td>
<td>83</td>
<td>D</td>
</tr>
<tr>
<td>canola, lupin and other legume crops, legume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pasture, volunteer pasture or chemical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fallow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farm arable area under cereals</td>
<td>%</td>
<td>36</td>
<td>E/D</td>
</tr>
<tr>
<td>Farm table area under break crops (canola,</td>
<td>%</td>
<td>36</td>
<td>E/D</td>
</tr>
<tr>
<td>lupin, sown fodder, legume pastures)</td>
<td></td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Arable area per full-time workers</td>
<td>ha/worker</td>
<td>36</td>
<td>E</td>
</tr>
<tr>
<td>Seeded area per worker present at seeding</td>
<td>ha/worker</td>
<td>35</td>
<td>E</td>
</tr>
<tr>
<td>Proportion of casuals workforce present at</td>
<td>%</td>
<td>36</td>
<td>E</td>
</tr>
<tr>
<td>seeding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proportion of family workforce who started</td>
<td>%</td>
<td>36</td>
<td>E</td>
</tr>
<tr>
<td>before 1985 and is actively engaged in farm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>decisions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enterprise diversity index(10)</td>
<td>%</td>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>

a Additional quantitative and qualitative data was collected but not used for this analysis.

b Included in the analysis only if covering more than 10% of the farm arable area.

c n.a. = non-applicable (qualitative information).

d Tested as D: dependent variable, E: continuous explanatory variable, EF: explanatory factor. Models tested for the selection of main effects were of the form: Linear models: D = a + EF₁ + EF₂ + b₁ + b₂ + . . . + bₙ + . . . + Eₙ; Mixed models: D = a + EF₁ + EF₂ + EF₃ + EF₄ + b₁ + b₂ + . . . + bₙ + c₁ + c₂ + cₙ; where i relate to farmers, j to soil types, n to the number of continuous explanatory variables included, and c to random error terms.

e Adapted from Lawes and Kingswell (2012): Simpson diversity index D = 1 - ∑pᵢ² where pᵢ is the proportion of farm area typically under enterprise i (number of enterprises: 8).
heavy soil types, that averaged, respectively, 2.2 t/ha and 1.9 t/ha (p = 0.025). The other respondents considered typical yields to be similar across soil types (overall typical wheat yield across 32 respondents: 2.0 t/ha ± 0.05 s.e.). Other differences in crop performance between soil types were seldom volunteered, and included 5 mentions about the higher potential of heavy soils (maximum yield attained with adequate pattern and amount of rainfall).

Exploration between soil types, grain yields and other farm characteristics using linear models led to only two significant sets of relationships:

\[ Y_{W} = 1.54 + 0.66L_{S} + 0.018C_{I} \]

\[ Y_{C} = 0.96 - 0.54H_{S} - 0.31R_{S} \]

where \( Y_{W} \) and \( Y_{C} \) are the typical farm wheat and canola yields, \( L_{S} \), \( H_{S} \) and \( R_{S} \) are the farm proportions of arable soil that is considered to be, respectively, light, heavy, and rocky. BC is the farm proportion of arable land typically sown under break crops (which covered on average 21% of the 36 respondents' farm arable area and included: canola 12%, lupin 4%, sown legume pastures 4%, miscellaneous sown mixed fodder 1%). The models are described in Table 5, while Fig. 5 shows the contribution of explanatory variables separately (partial models). No other farm variable from Table 4 was found to significantly predict farm soil composition, typical farm crop performance, or vice versa. However, some differences in overall wheat yields and soil composition were observed when contrasting farm types (Figs. 6 and 7). Mixed crop/sheep farms had more heavy, rocky and non-arable soils than specialist cropping farms. They also had lower wheat yields, if only slightly, which is consistent with the results of Table 5. However, further comparisons showed mixed farmers to have more consistent wheat yields (smaller range of high and typical wheat yields, Fig. 7).

3.3. Impact of soils on practices: rotation strategies

Different rotations were implemented on the different soil types. Other management differences were rarely mentioned. Five respondents did specify that heavy soils were sown first, but for others, seeding was prioritised by crop type, rotation stage and the weed burden. Differences in nutrients requirements were mentioned only twice (higher on light soils). In contrast, 90% of respondents who had different soil types specified conducting distinct rotations.

A total of 83 rotations were recorded from 33 farming businesses. Each rotation was characterised by a typical repeating pattern, of specific duration and composition, even those qualified as 'flexible'. On average, rotations lasted 3.4 years. Overall, the rotations were composed on average of 64% cereals, 20% break crops and 16% pastures/fallows. The occurrences of oaten hay, field peas and other crops were minimal. These results matched information collected with other means during an earlier survey (Table 6), notably confirming the importance of both pastures and canola as preferred break enterprises.

Nearly all the rotations recorded (93%) contained 50% or more of cereal crops. Their increasing importance had been highlighted by retired farmers who typically reported the following rotations: 1950s, 1 cereal out of 4 years (25%); 1970s, 1 out of 3 (33%); 1990s: 1 out of 2 (50%); down to the current situation with 2 out of 3 or 2.5 out of 4 (=65%). No permanent pasture was encountered on arable land, and pasture phases, most of them un-improved volunteers, rarely lasted more than a year. Similarly, no continuous cereal rotation was found, except for two occurrences on less than 10% of farm area which were thus not included. The vast majority of the 83 rotations (94%) broke the cereal phase after 1, 2 or 3 years (=20%, 40% and 35% of rotations, respectively). During exploration with mixed models, soil type and farm type as well as their interaction had strong effects on rotations most of the time (Table 7). However, none of the 20 continuous variables from Table 4 significantly explained differences in rotation duration or composition. The final models selected were therefore of the form:

\[ R_{i} = a + S_{i} + F_{i} + S_{i} \times F_{i} + e_{i} \]

or \( R_{i} = a + S_{i} + F_{i} + e_{i} \)

where \( R_{i} \) is the rotation variable (duration, compositions). \( F \) the effect of the farm type, \( S \) the effect of the soil type and \( e \) the error term (fitted as farms).

Fig. 8 summarises the rotation results. Wheat was by far the dominant enterprise in rotations for both farm types on all soil types. Light soils were managed similarly by all farmers, with 2 cereals, sometimes 3, followed by a break crop (cereals thus representing about two thirds of the rotation). Differences appeared on the other soil types, on which mixed farmers dedicated fewer years to cropping, essentially replacing some of the break crops by pastures. Furthermore, cropping specialists conducted significantly longer rotations on heavy soils, largely due to longer cereal phases.

Results are synthesised in Table 8 which provides the soil type composition for each landscape zone (see boundaries in Fig. 3), and the corresponding averaged rotations.

4. Discussion

4.1. Distinct rotation practices identified across soil types and farm types

Regional accounts of farmer production practices are rare in broadacre systems, in spite of their importance to understand rural dynamics. General agricultural dynamics are commonly reviewed,
Table 5
Coefficients and standard errors on the terms of the two selected linear models exploring relationships between farm yields, soils and other farm characteristics.

<table>
<thead>
<tr>
<th>Dependent variables: typical farm yield (t/ha)</th>
<th>Full model adj. R²</th>
<th>Intercept</th>
<th>Explanatory variables retained: proportion of farm arable area (%) under:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td></td>
<td></td>
<td>Light soils</td>
</tr>
<tr>
<td>n = 30</td>
<td>0.60</td>
<td>1.54 ± 0.08</td>
<td>0.007 ± 0.001</td>
</tr>
<tr>
<td>Canada</td>
<td>0.35</td>
<td>1.18 ± 0.05</td>
<td>n.a.</td>
</tr>
<tr>
<td>n = 17</td>
<td>(0.001)</td>
<td>(&lt;0.001)</td>
<td>(0.003)</td>
</tr>
</tbody>
</table>

a For the full list of 36 variables included, see Table 4.
b Coefficient of standard error: significance (p-values); n.a. non applicable (not selected in final model); n.t. not tested (dependent).
c Medium soils not tested since light + medium + heavy soils = 100% (dependent).
d Include: canola, lupin and peas, sow fedders (e.g. oats, hay), legume pastures.

Fig. 5. Linear relationships between farm grain yields and farm characteristics (partial models). Dashed lines represent predicted values of the positive effects of light soils and farm break crop area on wheat yields, and the negative effects of heavy and rocky soils on canola yields. The summed R² of the partial models are equal or inferior to those of the full models (Table 5), indicating that little overlap in explanatory power is likely to exist between the variables. The absence of correlation was also tested.

but little information is usually available that quantifies and explains the variability of practices within regions (e.g. Wolfe, 2011). In Western Australia, before the recent survey of Harmes et al. (2015), the latest regional information published was from 2004–2006 (Robertson et al., 2010). In both cases, results remained aggregated for large areas of the wheatbelt. This study cost-effectively provided a picture of current practices at a level of detail that has not been produced before, with results relevant for a large part of the central wheatbelt (Mortlock sub-region, Calloway, 2004). It confirmed that farmers alter their practices across the landscape within the farm, according to patterns that reflect the heterogeneity of soils (and their uneven distribution in that landscape). These differences in management primarily related to rotation strategies, with variations found across both soil types and farm type, in terms of composition and duration. Farmers conducted similar rotations only on light sandy soils, typically lasting 3–4 years, with 2–3 years of cereals and a year of break crops. On heavier soil types the proportion of break crops decreased, and was supplemented by pastures for mixed crop-sheep farmers and by cereals by cropping specialists. Specialist croppers also implemented longer rotations on these heavy soils, often adding a year of cereal (4–5 year rotation with 3–4 cereals). Evidently, farm-level considerations and fluctuations in weather and commodity prices are likely to modify the relative proportion of enterprises. For instance canola area had been increasing due to strong price signals, and an increase in long fallows may have been occurring as a risk management strategy (Oliver et al., 2010).

A first implication of these results is that the concept of “rotation” is not obsolete in Australia, in spite of the term “sequence” being more often used (Lawes, 2015b and references within). Crop and pasture successions are flexible, reflecting a highly variable environment, which explains why the term sequence replaced the term rotation. However, this study demonstrates that farmers do repeat patterns. In other words, opportunistic management does not completely override long-term agronomic planning.

Another implication relates to the definition of the landscape zones and broad soil types. The biophysical and management

Fig. 6. Proportions of soil types, other soil characteristics and typical wheat yields between farm types. p-values relate to differences in medians between cropping specialists who do not maintain any pasture on arable land (plain bars, n_max = 16, n_min = 12) and mixed crop-sheep farmers (dashed bars, n_max = 19, n_min = 20).
Fig. 7. Typical farm wheat yields. Typical high, usual and low yields a) across all farms; b) according to farm type, with tests on medians under the assumption that cropping specialists have higher yields than mixed farmers. The average yield range (between high and low yields) for cropping specialists and mixed farmers significantly differs and is, respectively: 1.76 ± 0.14 and 1.30 ± 0.13 t/ha (p = 0.002).

characteristics of these agro-ecosystems units confirmed that both spatial scales are necessary to capture and understand the observed diversity of farming practices. Importantly, these units are here disconnected from administrative boundaries. Local modelling studies have recognised links between soil types, production levels, and production practices (e.g. Kragt et al., 2012), however this study shows that their definition needs to be updated. Further implications of the rotation patterns identified are discussed next.

4.2. Continuous cereals are not a representative practice

This study demonstrated that continuous, un-interrupted cereal cropping is not a representative practice in the central region of the Western Australian wheatbelt. Similarly, continuous pasture is not practised on arable land in this region. This is contrary to common industry opinion, which is sometimes reflected in local farming system modelling (e.g. Robertson et al., 2010; Kragt et al., 2012). In fact, the vast majority of rotations described by farmers did not exceed a three-year cereal limit. Considering that cereals are the most profitable and reliable source of income, the main reason to forgo a year of production likely relates to ensuring the long-term sustainability of that production. This corroborates Harries et al. (2015)/'s survey which showed suitable levels for wheat production of weed density, soil borne pathogens and soil nitrogen, which were attributed to the frequency of non-wheat enterprises. It is also consistent with modelling studies showing that the probability of generating a profit strongly decreases after three years of continuous wheat (Lawes, 2015a), and that biotic stresses, particularly weed burden, force an increase in the proportion of break enterprises for long rotations to remain profitable (Lawes and van der Zee, 2015).

Yet, researchers' concerns about the sustainability of current cereal phases remain relevant. First, the overall lack of rotational complexity should be noted, the negative implications of which are well documented in Europe and the U.S. (e.g. Council of Europe, 2005; Philip Robertson et al., 2014). Only a few crop and pasture species were used, with no example of diversification encountered such as intercropping or cover crops (Atteri et al., 2015). Then, the observed level of 2–3 years of continuous cereals may only represent a stage, with trends showing that cereal production and farm areas were still increasing until 2012, in Western Australia and nationally (Fisher et al., 2010; Bell and Moore, 2012). Historical evidence collected during the exploratory phase of this study also confirmed the dwindling importance of non-cereal enterprises. By contrast, Foyer et al. (2016) reported that, worldwide, the increase in cereal production was largely due to greater yields from new agronomic practices and varieties, rather than increased area. Answering this question provides an argument for monitoring rotation practices throughout time.

4.3. Farm soil composition and break crop area are determinants of farm grain yield

The majority of farmers could not propose a typical yield difference between the soils on their farm. However, farm grain yields were found to vary in relation to soil composition (canola R² = 55%, wheat R² = 32%). Farm canola yields decreased with the amount of heavy and rocky soils on the farm; predicted farm wheat yields were 0.5 t/ha higher when most of the farm was composed of light soils (80%), compared to farms which only had little (10%). This difference is substantial as regional averages are only about 2.0 t/ha, and as wheat yield is a prime driver of long-term success for farm businesses (Lawes and Kingwell, 2012; Kingwell et al., 2013). Apart from break crops, none of the other 36 farm characteristics tested was as important as soils to explain the variability in these typical farm grain yields. Therefore, in spite of rarely being included, farm soil composition should not be neglected when studying farm performance.

Table 6

<table>
<thead>
<tr>
<th>Studies</th>
<th>This study</th>
<th>Harries et al. (2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of study area</td>
<td>4 000 km²</td>
<td>approx. 12 000 km²</td>
</tr>
<tr>
<td>Data</td>
<td>83 typical rotations</td>
<td>65 fields information across 4 years</td>
</tr>
<tr>
<td>Data collection procedure</td>
<td>Farmer interviews, 2014 (approx. 2 months)</td>
<td>Yearly monitoring, 2010–2014</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overall proportion of rotations* under each enterprise</th>
<th>This study</th>
<th>Harries et al. (2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal (Wheat + Barley)</td>
<td>64 (50 + 14)</td>
<td>66 (58 + 8)</td>
</tr>
<tr>
<td>Canola</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Legumes (Lupin + Peas)</td>
<td>8 (7 + 1)</td>
<td>&lt;7 (5 + 1)</td>
</tr>
<tr>
<td>Pastures</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Fallow</td>
<td>&lt;2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Others</td>
<td>&lt;1</td>
<td>&lt;3</td>
</tr>
</tbody>
</table>

* Slight differences with farm acreage area proportions can be noted due to rotations not being adjusted for area.
Table 7
Effects of soil type and farm type on the duration and composition of rotations.

<table>
<thead>
<tr>
<th>Rotation variable*</th>
<th>Soil type (Heavy, Medium, Light)</th>
<th>Farm type (Cropping, Specialist, Mixed)</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (rotation year)</td>
<td>n.s.</td>
<td>*</td>
<td>***</td>
</tr>
<tr>
<td>Composition of rotation (%)</td>
<td>Wheat n.s.</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td></td>
<td>Barley n.s.</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total break crops **</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Canola **</td>
<td>***</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>Lupin ***</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>Pastures ***</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Chemical fallow n.s.</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
</tr>
</tbody>
</table>

*Mixed models, n=83 with farms (n=33) sets as random effects.
p-values for categorical variables: *<0.001, **<0.01, ***<0.05, ****<0.1, n.s.>0.1.
n.a. not applicable, since mixed farmers have pastures but no chemical fallows, and vice versa for cropping specialists.

Overall, 90% of farmers who had different soil types conducted different rotations on at least two of them.

Whilst rarely able to specify yield differences, farmers’ comments regarding the performances of their different soil types was nevertheless consensual and can be summarised as “heavier is better in good (higher rainfall) years, but light is more reliable in dry conditions, which is more common”. This is consistent with McBeath et al. (2015)'s experimental results and Hochman et al. (2009)'s observations when measuring wheat use efficiency on soils of varying plant available water capacity. The respondents’ difficulties in pinpointing actual wheat yield differences may be a reflection of the high seasonal variability of rainfall which impact was also shown, in Western Australia, to vary across soils with plant available water capacity (Lawes et al., 2009). It indicates the limitation of questionnaires when addressing the topic of long-term farm performances, and the interest of collecting more detailed information.

The area of break crops at the farm level also contributed to explain typical farm wheat yields: a difference in the order of 0.5 t/ha was predicted between farms with 5%–40% of arable area planted to break crops, mostly canola and lupin. Although these crops are primarily grown on light soils, their effect was largely shown to be additional. The importance of breaking the cereal phase with the growth of an unrelated crop species is well demonstrated, including in no-till Mediterranean environments (Seymour et al., 2012; Altieri et al., 2015; Angus et al., 2015; McBeath et al., 2010; Ruisi et al., 2016). However, most studies and surveys measure the impacts of non-cereal break enterprises on wheat yields at the field scale; this study provided evidence at the farm scale. Pastures may also contribute a break effect since they sometimes replace break crops, as suggested by Robertson et al. (2010) and (Lawes, 2015b). Here this was done by mixed farmers on heavy soils, however no evidence of pasture impact on farm wheat yields was found.

Lastly, it can be noted that differences in nutrient requirements did not appear to be a salient production issue. This suggests a reason why variable rate fertiliser applications are not widely used (Robertson et al., 2012); in study area: <10% adoption).

4.4. Farm soil composition influences cropping specialisation (farm type)

With continued trend in relative prices that had been favouring cereals instead of livestock products, farms in southern Australia have gradually become more crop-intensive (Wolfe, 2011; Bell and Moore, 2012). In this study, nearly half the farmers were 100% cropping. This contradicts the suggestions of Villano et al. (2010), Colas (2011), Wolfe (2011) and Kirkegaard et al. (2011) that cropping specialists were unlikely to rise in significant numbers, due to the production synergies and risk mitigation attributes of mixed systems.

Although several respondents stated the change was not set in stone, practically the decision is not easily reversed due to changes in field sizes, labour requirements, fencing, machinery, buildings, and naturally, livestock investments. In fact, no situation was encountered where these farmers had brought back livestock, even though prices had recently risen for some livestock commodities. Deciding to abandon animal production has thus very different implications than opportunistically altering the farm crop/pasture mix. However, whilst many studies investigate the determinants and impacts of changing that ratio, in Australia (e.g. Colas, 2011; Moore et al., 2011; Krug et al., 2012; Rodriguez et al., 2014) and in developed countries internationally (Le Gal et al., 2011), there is a lack of research regarding the drivers that motivate or hinder the commitment to what appears to be a permanent system change.

The results of this study suggest that the decision to abandon sheep and specialise in cropping only is influenced by farm soil composition: mixed crop-sheep farmers had (i) more heavy land, which has become increasingly less reliable for cropping due to lower and more variable rainfall, (ii) more rocky land, where crops

![Fig. 8. Duration and composition of rotations typically conducted in the study area. Farms included: 33 (42% cropping specialists, 58% mixed farmers). Typical rotations identified: 83, each implemented over at least 10% of the farm arable area.](image-url)
Table 8
Synthesis of landscape and management heterogeneity: soil types and rotation strategies.

<table>
<thead>
<tr>
<th>Dominant soil types</th>
<th>Light</th>
<th>Medium</th>
<th>Heavy</th>
<th>% arable in study area</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC/CJB</td>
<td>35</td>
<td>45</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>B+C/J</td>
<td>35</td>
<td>45</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>CCC/J</td>
<td>35</td>
<td>45</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Valley floors</td>
<td>15</td>
<td>35</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>% arable in study area</td>
<td>30</td>
<td>40</td>
<td>30</td>
<td>100</td>
</tr>
</tbody>
</table>

See map Fig. 3 for the localisation of the zones in the landscape. Percentages are approximate. Arable area = %; Rotations: C=Cereals (%: wheat, barley), B=Break crops (%: canola, lupin), P=Pastures (mainly volunteers), X=chemical fallow. For instance, CCC/JB is equivalent to ‘2–3 cereals followed by a break crop’, with cereals sown 2.5 years out of 3.5 and thus representing 70% of the area under that rotation. Hilly sandplains feature more rocky areas than the two other zones (~20% vs. 3%), and valley floors more non-arable land (~15% vs. 8%). Soil types and landscape zones are further described in Table 2 and Table 3.

are more difficult to grow (lower plant available water, slower operations due to machinery damage and lesser manoeuvrability), and (iii) more non-arable land which is only productive if used as a permanent extension of pastures. This is consistent with general observations made by Kirkgaard et al. (2011) and Bell and Moore (2012).

Retaining sheep can therefore be interpreted as a strategy to cope with having greater proportions of poorer resources, i.e. more land unsuited for cropping or with lower typical production levels. On heavy soils, cropping specialists implement longer cereal phases, perhaps compensating lower long-term grain yields with an extra year of cereal that is permitted by the higher fertility of fine-textured soils. However, profitability difference may lie with the break enterprises, which are difficult to grow on these soils. Whilst cropping specialists seem to increasingly rely on occasional low-cost fallow options, sheep production and the minimal cost incurred by volunteer pastures may represent a more profitable option, as suggested by Robertson et al. (2010). Inversely on "premium" light soils, mixed farmers implemented the same cereal-intensive rotations as cropping specialists.

These pragmatic drivers are significant because social factors are generally seen as overriding in land use decisions and production orientation, particularly individual attitudes to risk and personal preferences toward animal work (workload, handling, holidays, etc.) (McLeod and Rickards, 2011; Wolfe, 2011). Increasing the farm cereal area through rotations to increase long-term profit (Lawes and Kingwell, 2012) may not be possible on all farms to the same extent. Crop specialisation may thus not be in the interest of every farmer. This supports the outputs, used in the local MIDAS and UJOS models and more generally in farming system design, that different sets of farm resources, here soils, results in different opportunities to maximise profit at the whole-farm level (Le Gal et al., 2011; Moore et al., 2011; Bell and Moore, 2012; Martin et al., 2012; Kingwell et al., 2013; Lawes and Renton, 2015).

4.5. Location-dependent soil compositions and farming trajectories

As well as being linked to production orientation and grain yields, farm soil composition was shown to depend on the location of the farm in the landscape, which is consistent with Robertson et al. (2009)'s observations. Confirming this is the observed distribution of farm types: mixed farms represented 56% of the sample overall, but only 31% of the farms located in the zone of undulating sandplains, vs. 73% in the hilly sandplains and valley floors where heavy, rocky and non-arable soils were more common.

This is particularly significant when considering that 88% of the farms in the sample were inherited, 91% of these tracing back to settlement times (1900s), and that most farm expansions occurred in the vicinity of the original family farm. The practical implication is that distinct farming trajectories may be identified, i.e. path dependencies that explain some of the differences observed today (Sutherland et al., 2012; Lyle, 2015). This is in spite of settlement policies in the Western Australian wheatbelt that had been, very much like the Homestead Act of the 19th century in the US, particularly equalitarian (Lindsay, 1957; Coles, 1969; Rankie, 2005; Shanks, 2005; Appleyard and Couper, 2009). When the farm history led managers to access a riskier situation (heavy soils, typically in valley floors), the strategy focuses today on securing production (mixed crops/livestock); when a safer situation was inherited (light soils on sandplains), opting for cropping specialisation is less risky. Furthermore, the different grain production levels may affect farm returns and, over time, investment opportunities including farm expansion or technological advances (Kingwell et al., 2013). The findings of Kingwell et al. (2013), Thompson (2015) and Hughes et al. (2011) suggest this has been the case in Western Australia and across the country, with crop-dominant farms found to grow financially more secure than livestock-dominant farms, with greater cash income and total factor productivity.

Acknowledging that some sets of farm resources, here soils, are for a large part inherited and impact current practices has important implications. First, taking into account this farming constraint could contribute to the design of realistic development and extension projects. For instance, diversification as a pathway to mitigate climate change impacts and economic pressures (Wolfe, 2011; Alterri et al., 2015) is here not possible to the same extent to all farmers, in spite of sharing the same climatic zone and economic environment. Then, recognising the historical component of this farming constraint could alleviate self-doubt and the stigma that sometimes surrounds productivity stagnation (Hogan et al., 2012). More generally, it could contribute changing the reliance on value judgments to explain farmers’ management choices. Disparaging discourses have been enduring across time and countries (Handy, 2009), with farmers often adopting the rhetoric themselves even in developed countries. For instance in this study, when asked why they retained sheep in spite of their seemingly lower profitability, no respondents mentioned soil types but many volunteered their “own laziness” or “irrational preference for animals” as explanations.

4.6. Further value of comparative agriculture for research and development

This study showed that the mixed methods of comparative agriculture could complement other approaches, such as consultant databases (e.g. Lawes, 2010) and multi-year surveys (e.g. Harries et al., 2015), when studying farming practices and performances, at both farm and landscape scales. Here, the approach was useful to demonstrate variations in rotation strategies across an heterogeneous landscape (in spite of low rotational diversity), and the importance of soil profiles to farm production orientation and farm grain yields. This is significant as most studies either assume these relationships in models, or measure them in given fields, not at farm-level. Other valuable contributions include providing baseline information, monitoring tools and land division criteria. Importantly, detailed farm and practice information was collected while keeping research costs...
low (one investigator over a few months, as opposed to multi-year surveys), the sample was ensured to be representative of the regional population, and common sampling and response survey biases were actively reduced (e.g. participants self-selection, under-coverage, peer-pressured answers and social desirability, irrelevant questions and questionnaire structure, surrogate errors, etc.). This was achieved by focusing on farmers’ practices rather than discourses, and by using three techniques that are rarely used in Australian agricultural research, particularly when investigating technical aspects (Lacoste et al. in press): iterative prioritisation, historical investigation, and progressive criteria definition.

The ability to rapidly collect varied farm and practice information dominating different parts of a landscape could contribute baseline data for model calibration or validation exercises. Typically, comparative agriculture is used to assess farming system diversity, to model representative farming systems, to calculate their economic and technical performances, and to propose realistic scenarios for both simulation modelling and project design, using the local knowledge gathered during the procedure. Barnaud et al. (2008) and Moreau et al. (2012) provides examples of these five applications for the integrated assessment of watersheds in Thailand and in France, respectively. In the present study, the rotation information collected can also help decide realistic controls in crop sequence experiments. For instance, it was shown that permanent pastures are not a representative local practice anywhere on arable land; and that rotations representing mixed and crop-only systems should be differentiated except on light sandy soils.

The methods of comparative agriculture could also be used as a relatively quick and non-expensive monitoring tool to assess agricultural trends. For instance in this study, the 6 arable soil types originally identified by retired farmers proved comparable to the 8 land management units distinguished when modelling a typical farm in the central wheatbelt of Western Australia (e.g. Robertson et al., 2010; Krägt et al., 2012). However, only 3 of these arable soil types were contrasted due to lack of differences in current management, in spite of the high local heterogeneity of soils. This signals a trend towards simplification of management in terms of land use and practices. It is consistent with observations made in other developed broadacre farming regions worldwide where farm size increases while the availability of qualified and even unqualified labour decreases due to rising non-agricultural wages (Mazoyer and Roudart, 2007; McGucklan and Rickards, 2011; Deininger and Byerlee, 2012). Alternatively, the synthesis map produced can be easily be used to estimate areas for potential practice change or for the suitability of given innovations in project and policy planning (e.g. assess the proportion of heavy soils in the landscape where rotations may be modified with new suitable crop or pasture species). An advantage of this simple synthesis is the straightforward communication of outputs to non-specialists, including decision-makers. Another application would be to contribute to the extrapolation of field measurements to larger scales by stratifying farm and field samples per landscape zone, as suggested by House et al. (2008).

Finally, the integration of historical, landscape, farm and field dimensions is of particular interest given the lack of quantitative approaches that juxtapose different spatial and temporal scales (Dale et al., 2012). The inclusion of farm management criteria in the definition of landscape zones could complement other approaches to landscape characterisation, since most are solely based on biophysical information (Alexandra, 2012). Here, this led to some differences in definitions and boundaries when comparing the three landscape zones identified to the landscape systems of existing maps. Together with Galloway’s sub-regions (2004), meaningful landscape divisions could thus be produced to complement the standard climatic grid partitions of the wheatbelt. This could for instance inform the management aspects used to calculate regional yield gap maps (Hochman et al., 2012).

5. Conclusions

This study highlighted the potential of a method that deserves wider application. Comparative agriculture, novel in broadacre agricultural research, proved useful to simplify the complexity of a highly heterogeneous landscape, to answer whether the different parts of this landscape are managed differently, and to quantify the extent of these differences. Some of the results generated could also prompt thinking around some common assumptions regarding the drivers of farmers’ strategies (e.g. individual skills or preferences vs. historical reasons), which could lead to changes in how some analyses are conducted. Outputs could also complement surveys and consultant databases to define typical farming system attributes, monitor practices, and contribute meaningful divisions of relatively large agricultural landscapes.

The open nature of the data collection permitted to consider a wide breadth of factors when investigating practices and performances across the studied area, while ensuring the information remained both detailed and representative of the farming population. The rotation strategies of farmers were found to vary across the agricultural landscape according to distinct patterns; mixed models showed differences in rotation duration and enterprise composition between farm types and across soil types. However, similar rotations were conducted on light sandy soils by both cropping specialists and mixed crop-livestock farmers. Linear models showed that the impact of soil type on grain yield scaled up at the farm level, with typical wheat and canola farm yields linked to the farm soil composition. Lights soils may have lower potential production levels than fine-textured heavy soils, but in a context of low and variable rainfall their reliability translated to longer-term yields. Soil composition was also shown to impact the production orientation of farms, i.e. the decision to remain mixed crop-livestock or entirely specialise in crops. The latter was found to apply to nearly half the farms of the sample, with no examples of reversal to mixed farming. Farm soil composition varied across the landscape with distinct zones identified, and so was the distribution of farm types. Together with farm heritage and expansion patterns, this information highlights the importance of farming trajectories in explaining regional variations in current performances and practices, including the observed divergence in production orientation: the position of the original family farm is likely to impact current soil composition and therefore farm grain yields, as well as the decision to specialise or not in cropping only (inherited risky heavy-textured land favours crop/livestock mixes, whilst safer light soils permit riskier cropping specialisation).

Acknowledgments

This work was funded by the Australian Government, Department of Education (IPRS/APA scholarship), and by the Grains Research and Development Corporation of Australia (GRDC, GRS scholarship). The authors also thank: Stephen Powles for his continued support; Matthew McNeel and two anonymous reviewers for comments on the manuscript; personnel from DAFWA (Department of Agriculture and Food Western Australia), DoW (Department of Water) and Wheatbelt NRM (Natural Resource Management, Landcare) for the provision of local maps and information; as well as Shauna Wells, Chris Syme, Dennis and Glenda Pease for valued field support. The authors would also like to sincerely thank all the farmers who contributed their time to this study, and the town of Wyalkatchem for the constructive cooperation of its residents.


The relevance of comparative agriculture was demonstrated,
its performance in assessing regional diversity was validated,
and new knowledge about Australian farming systems was produced.
5.1 Summary of key findings and local implications

The main hypothesis of this thesis was to determine whether the discipline of comparative agriculture could improve the assessment of regional farming system diversity in Australian broadacre regions, and thus make valuable contributions to Australian farming system research. This was shown by producing new knowledge about both local research practices and farming systems. Specifically:

- The *methodological relevance* of comparative agriculture was confirmed by showing that the tools of comparative agriculture were novel in the Australian agricultural research context. Furthermore, methodological, conceptual and topical gaps were shown to exist (relatively little use of mixed methods and holistic frameworks, and few studies integrating social and technical topics), that comparative agriculture could contribute to bridge.

- The *methodological capability* of comparative agriculture was confirmed. Its concepts and methods assessed regional farming diversity holistically more effectively than the mainstream methods currently used by scientists and other agricultural professionals. To start with, data was collected more cost-efficiency, more comprehensively and with more control over its quality than allowed by industry surveys and consultant databases. Then, greater insights about how the local farming systems differed from each others were provided compared to the outputs of standard multivariate techniques. That information permitted to establish new linkages regarding the organisation of farm resources (farm soil profiles, rotations, grain yields), leading to an improved understanding of farmers’ practices and of some of the complex relationships that exist within farming systems. This new knowledge has, as discussed in the previous chapters, multiple applications for local research, development and extension. Examples include improved spatial divisions of the wheatbelt, identification of landscape zones, criteria for survey designs, set up of representative field trials, definitions of farm groups for model parameterisation (*Fig. 1*), changes in extension messages with the idea of farming trajectories, promotion of specific investments e.g. research in labour-saving practices, and evidence to target policies e.g. support for young farming families and “semi-retired” farmers, drought relief for vulnerable businesses, incentives for socially and environmentally sustainable systems, etc. (*Hamblin, 2009*).
Fig.1. Farming system typology: examples of application for model parameterisation (modified from the Fig. 6 of Chapter 3).

Models representing agricultural systems in the central Western Australian wheatbelt should use 6 farm types which typical characteristics and range of existence can be conveniently extracted from the typology (a). These characteristics include farm resources (area, equipment, labour), and a range of practices (e.g. enterprise mix, vertical integration, etc.) (b). Results also show that the largest farms (c) should not be used as case studies: they must be included to account for the heterogeneity of the region, however they do not represent the majority of farming business situations. Example of relevant models which parameterisation could be improved by using this information include RIM (e.g. Lacoste & Powles, 2014, 2015, 2016), MIDAS (e.g. Kragt et al., 2012; Thamo et al., 2013)) and APSIM (e.g. Ridoutt et al., 2013; Ghahramani & Moore, 2016).
5.2 Broader significance of the work and limitations

By endeavouring to introduce a new discipline to a research community, this thesis represents an original contribution to agricultural scholarship.

From a wider perspective, this work is also the first in-depth study comparing the agrarian diagnosis methods of comparative agriculture with mainstream statistical tools. It is also the first trialling of an interpretative review for farming system methods.

In addition to their local implications, the outputs presented here also hold wider significance in different ways:

- **Wider application of comparative agriculture worldwide**: Increased evidence that comparative agriculture is relevant to the study of broadacre situations worldwide. Few comparative agriculture studies had been conducted in such environments before, none of them published in peer-reviewed English-speaking literature until now.

- **New practical tools to answer novel research questions and produce new knowledge**: Comparative agriculture provided answers to questions which current methods did not address adequately (related to farmers practices, notably), with the potential to thus expand the scope of applied research (in Australia to date, systemic holistic efforts that take into account the varied and multi-scale aspects of farming have mostly been represented by modelling studies).

- **New review tools to identify research gaps and inform research investments**: The interpretative review procedure can provide novel, synthetic overviews of research efforts about a given topic that decision-makers can use to target future investments.

- **Identification of methodological gaps in Australian agricultural research**: Besides those of comparative agriculture, other holistic approaches and mixed methods frameworks deserve increased attention in Australia as to the contributions they could make, notably social-ecological systems, evolutionary economic geography, political ecology.

The main limitation of the work presented in this thesis is the application to a single study area. Caution must be exercised when generalising findings to broader regions. However, this is a stepping stone for additional studies. Furthermore, tools were provided in Chapter 3 to conveniently collect additional information for further validation (farming system characteristics and classification rules).
5.3 Future research directions

With regards to the thesis as a whole, additional diagnostics must be conducted in other Australian regions to be able to extent the results. Similarly, further comparisons of the agrarian diagnosis vs. statistical methods should be made in other agricultural contexts.

Otherwise, the interpretative review procedure deserves to be applied to other challenging, multi-disciplinary topics in agriculture. Alternatively, the same study could be conducted for other research communities, to allow comparisons of, for instance, Australian, European and American research practices.

With specific regards to outputs produced, suggestions for applications were made in Chapter 4. Numerous other topics could be further investigated as well if further funding was available. The following areas can be highlighted.

• **Further discussion and development of a farming system framework**

  Numerous aspects were investigated and shown to differ across farming systems, as shown in Fig. 8 of Chapter 3. Only a fraction of the implications was discussed in Chapter 4. Other aspects could be developed, notably regarding the reasons why low diversity exists in Western Australia (in contrast with most regions of the world), or why certain practices are not adopted by all types of farming systems (notably early sowing, on-farm grain storage, precision agriculture technologies, off-farm asset diversification).

  Further researching these aspects could inform the development of a synthetised framework, that could enrich the current perspective about Australian broadacre farming systems. This novel farming system framework could then serve as a basis to justify the investigation of particular aspects, with examples below.

• **Future research projects: farming practices**

  Areas of interest identified during this study that could warrant further data collection include: further assessing the relationships between the nature of labour and the process of cropping specialisation; investigating factors and thresholds for transitioning between types of farming systems e.g. from “standard” to “large”; assessing further the level of adoption of practices e.g. early sowing, on-farm storage, etc.; evaluating the economic value of practices e.g. herbicide application vs. sheep grazing for weed control.
• Further analysis: technical and economic performances

An aspect that particularly deserves further consideration is the topic of performances. The considerable amount of data collected in the applied study could be further analysed without the requirement for additional fieldwork. This includes detailed pricings and costings that were not presented. No such information was encountered in the literature, and standard sources such as consultant databases do not provide the same level of quality. This information could be used to calculate the technical and economic performances of the farming systems identified in the study area, allowing a range of topical research questions to be addressed regarding efficiency, capacity, vulnerability and resilience. This assessment could then be compared with existing research or other diagnostics, within Australia and with other parts of the world.

• Further interpretation: co-existence of farming systems and regional dynamics

Chapter 4 demonstrated how comparative agriculture can help gain insights in some complex relationships within farming systems. An aspect not developed in this thesis is how results on farming diversity can lead to insights about relationships between farming systems, with regional implications. Differences in farming resources are likely to result in different abilities to adapt to challenges, which impacts farm trajectories. For instance, transfers in land and capital occur when farming businesses exit the industry. Similarly, changes in human capital may follow differential trends in technologies and practice adoption. A dynamic interpretation of how each farming system may evolve, and of the conditions for their co-existence, could provide valuable insights in the agricultural future of the region.
5.4 References


Concluding notes

I would like to conclude this thesis by highlighting the success it represents, academically and personally.

First, it has been my strong (informed) opinion for the last decade that comparative agriculture deserves to be better known in English-speaking academia. This thesis finally provides evidence of the valuable contributions the discipline can make in a context that agricultural scientists in Australia and other developed countries can relate to.

Second, concluding this thesis rewards 8 years of perseverance amidst peers who had never heard of comparative agriculture. I waited, gained experience, persisted, convinced senior researchers and funding bodies. At last, 3.5 years ago, I was able to design and start this PhD project on my own terms – against the commonly given advice of choosing a “less risky”, “more mainstream”, “less nebulous” topic.

It is my hope to have convinced readers of the value of comparative agriculture, and to be able to continue the initial momentum produced by this work.

To do this, funding organisations and decision-makers who are not familiar with these methods must be convinced. This is challenging considering that mixed and qualitative methods are still regarded as second-grade tools in agricultural sciences.

In addition, human capacity must be invested in. The cost-efficiency of the methods was demonstrated (investigator, resources and time vs. quantity and quality of the outputs), however the initial training costs are high. Comparative agriculture requires education across several disciplines in addition to specific training in its methods. As of 2017, only the institutions of AgroParisTech and Montpellier SupAgro in France had education departments sufficiently equipped to teach comparative agriculture graduates. Proactively attracting scholars and students from these institutions is a necessary preliminary step to the development of capacity in Australia and other non-French speaking academic communities.

The diffusion of comparative agriculture requires further perseverance, which is well worth it, for the opportunities it presents to agricultural sciences and the industry!

Chidlow, January 2017
All references


Emtage, N. & Herbohn, J. (2012). Assessing rural landholders diversity in the Wet Tropics region of Queensland, Australia in relation to natural resource management programs: A


