Agriculture, Ecosystems and Environment 233 (2016) 381–395

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Comparative agriculture methods capture distinct production practices across a broadacre Australian landscape

Myrtille Lacoste[a,*], Roger Lawes[b], Olivier Ducourtieux[c], Ken Flower[a]

[a] University of Western Australia, School of Plant Biology, Crawley, WA 6009, Australia
[b] CSIRO Ecosystems Environment, Floreat, WA 6014, Australia
[c] AgroParisTech, UFR Comparative Agriculture, UMR PRODIG, 75231 Paris Cedex 05, France

ARTICLE INFO

Article history:
Received 25 February 2016
Received in revised form 3 September 2016
Accepted 19 September 2016
Available online 5 October 2016

Keywords:
Soil heterogeneity
Land use
Rotation
Sequence
Farmer
Mixed methods

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^2 area in a region of the Western Australian wheatbelt (≈300 mm/year) with highly variable soils.

Land types influenced 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/fallows. Break crops were grown more 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 farm 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 agricultural landscapes are also discussed.

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

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

http://dx.doi.org/10.1016/j.agee.2016.09.020
0167-8809/

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 Kingwell, 2012; Kingwell 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; Rodriguez 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;

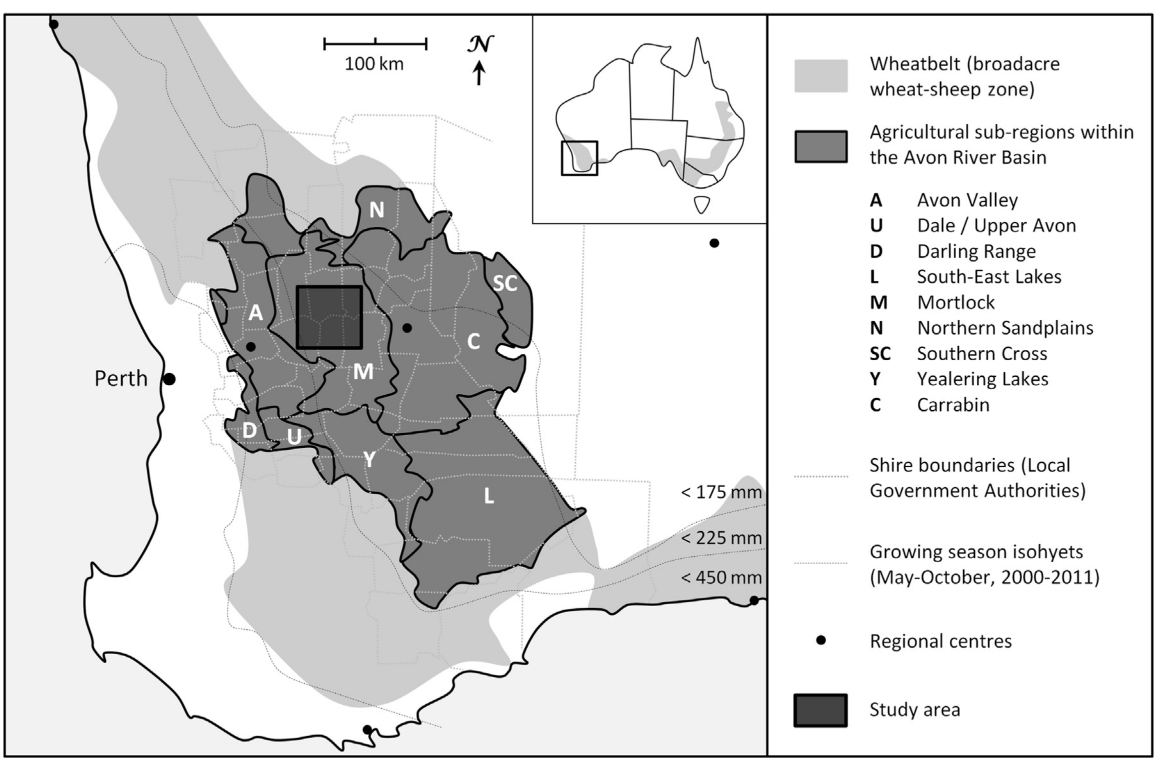

Fig. 1. Central Western Australian wheatbelt and study area.

Sources: DAFWA (2014); Galloway (2004).

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 4 000 rainfed broadacre farms. This includes a third of the country's wheat tonnage, produced with yields slightly less than 2 t/ha on average (ABARES, 2014). The study area occupies approximately 4 000 km^2 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 (Galloway, 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 multidisciplinary aspects, notably by collecting both quantitative and qualitative information on a variety of topics. Third was to

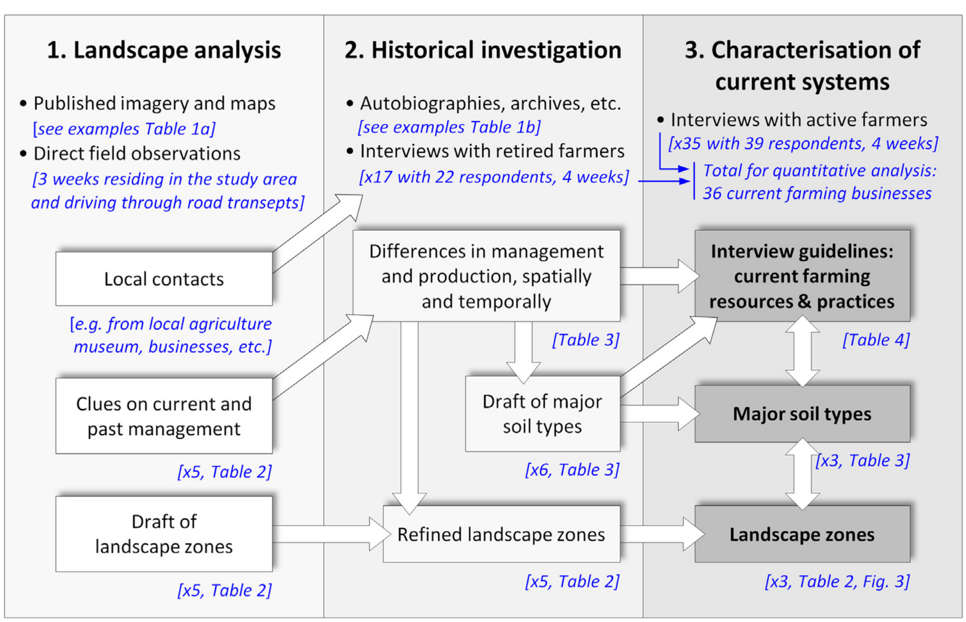

Fig. 2. Data collection procedure (agrarian system diagnosis).
Respondants are identified while scouting the study area, using maps and snow-balling. Selection is random stratified within landscape zones, recruitement is by cold-calling. Interviews are semi-structured and in-depth. Interview duration and respondant 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.

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 transepts. 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

Table 1
Criteria initially considered to contrast homogenous landscape zones.

Type	*Criteria*
a) Landscape analysis (existing material and field observations)	
Morphology	Elevation, relief, overall landscape shape (e.g. hills, plains, ridges, rocky outcrops)
Geology	Base rocks, mines
Pedology	Soils
Hydrology	Rivers, creeks, ponds, aquifers, water flows and regimes
Vegetation	Land cover, native and introduced species, micro-climates
Land use	Crops, pastures, plantations, reserves, shape and size of fields, seasonal agricultural activities
Housing	Location and nature (e.g. grouped, dispersed, abandoned)
Infrastructure	Transport network, buildings (e.g. storage), power and water supply, dams
Administrative divisions	Local government boundaries, cadastral plans
b) Historical investigation (retired farmers interviews and archives)	
Main events	National and local that impacted the area e.g. settlement, wars, industries booms and collapse, policies, droughts, etc.
Demographics	Population trends, migrations, exodus
Commodities and services	Price trends, access, markets
Technologies	Water and power access, mechanisation, germplasm, electronics, chemical inputs, etc.
Techniques	Rotations, land preparation, seeding dates, fertility renewal, weed control, etc.

Notable published sources relevant for this study included: a) Geoscience Australia, 1970a,b; Mulhling and Thom (1985); Lefroy et al. (1991); Lantzke and Fulton (1992); McArthur (1992); Lantzke and Fulton (1993); Grealish and Wagnon (1995); Verboom and Pate (2003); O’Byrne (2009); Sawkins (2010); Schoknecht and Pathan (2013); Verboom and Pate (2013); Doncon (2014); Google (2014). b) Appleyard and Couper (2009); Coles (1969); Lindsay (1957); Rance (2005).

Table 2
Landscape zones identified in the study area using published material, direct landscape observations and interviews with retired farmers.

Final landscape zones	*Undulating sandplains*	*Hilly sandplains*	*Valley floors*
Initial 5 zones drafted (and corresponding WA landscape systems)	• "North-East sandplains" (Tangedin) • "South-West sandplains" (Phillips)	• "North-West sandplains" (Kwolyin) • "South-East hills and sandplains" (Kwolyin)	• "Valleys" (Kellerberrin and Wallambin)
Elevation (a.s.l.)	250–300 m	250–350 m	200–250 m
Morphology (see Fig. 3)	Undulating, open country	Generally steeper, more frequent vegetation, rocky outcrops and gravelly crests	Generally flat, salt lake system and tributaries secondary beds
Dominant geology (see Fig. 3)	Colluvium, laterite, granitic rocks	More granitic	Alluvium
Land use	Crops	Crops, more pastures, rocky reserves	Crops, more pastures, saline reserves
Cadastral pattern	Regular, large fields	Varied, mostly smaller and irregular	Varied, mostly smaller and irregular
Road network pattern	Secondary, regular grids	Secondary, irregular	Primary. Major townships.
Dominant native vegetation cover	Bushes	Varied	Large trees and mallee formations
Historical highlights	Second clearing phase (1960s), value increase after production increases with ameliorants (1970s), no townships	Second railway. Early developments (rock water pools)	First settlements (1900s), developments (clearings, fencing, water), transport incl. first railway

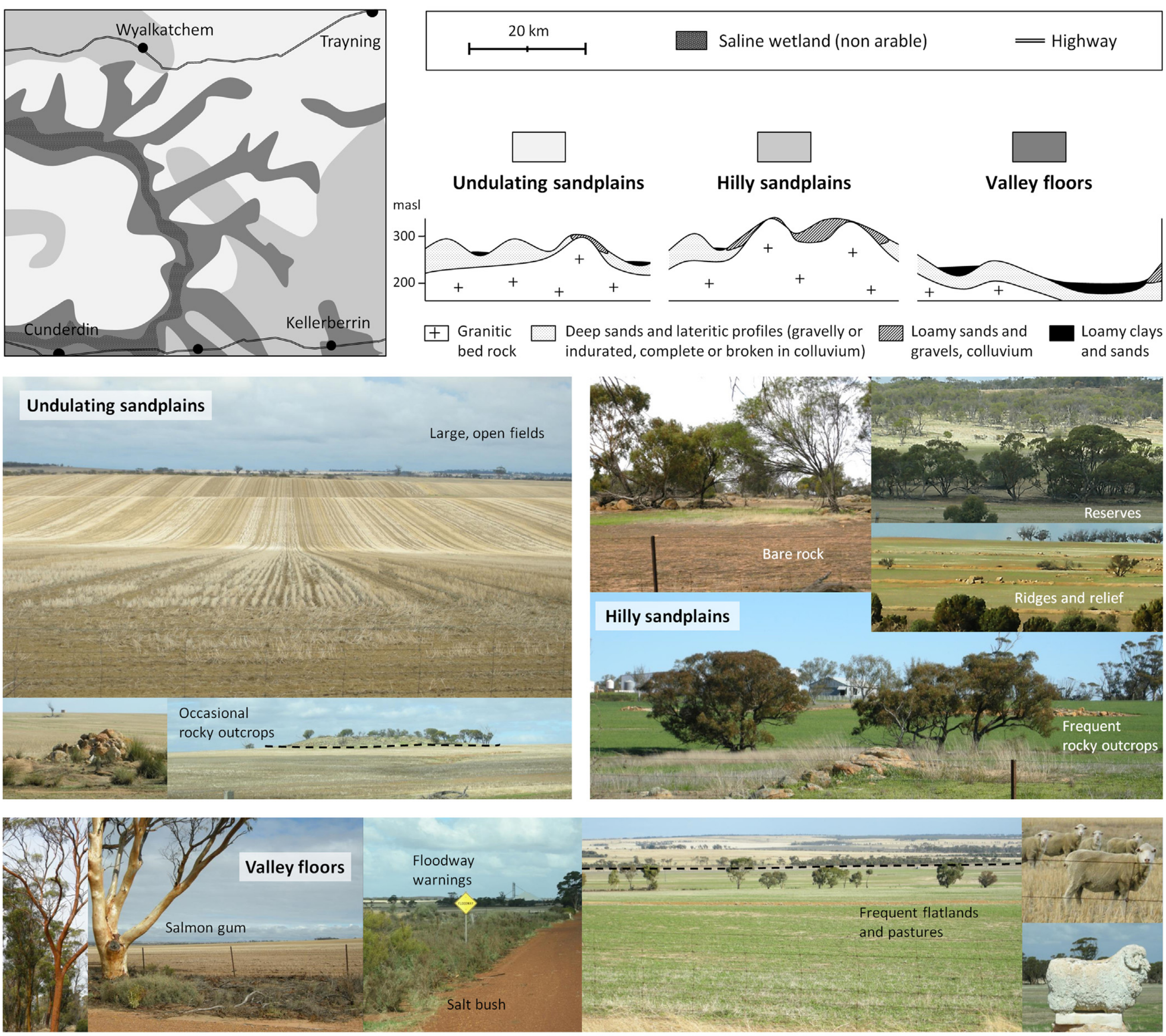

Fig. 3. Landscape zones identified in the study area.
Boundaries, schematic cross-sections with dominant morphology and geology, typical features.

Table 3
Major arable soil types identified in the study area during interviews with retired and active farmers.

Final soil types	*Light*	*Medium*	*Heavy*[#]
Initial 6 soil types, local names	• "Tamma country" • "Wodjil/gutless sands" (small areas)	• "Mixed medium soils" • "Jam country" (both managed similarly)	• "Timber/gimlet/salmon gum loams" • "Blue/grey/red clays" (small areas)
WA soil types	Deep sands, gravelly sands, sands over loams or gravels (duplexes)	Similar to light soils with more shallow loams and sands, and more rocks	Loams, loamy clays and sands, clays, saline, sodic and waterlogged areas
WA soil landscape unit classification	Ulva, Booraan	Danberrin, Collgar	Belka, Nangeenan, Baandee
Australian soil classification	Chromosols, kandosols, sodosols	Sodosols, chromosols, kandosols, dermosols, rudosols	Sodosols, vertosols, dermosols, hydrosols
Distinctive vegetation	Black tamma (*Allocasuarina acutivalvis*), wodgil (*Acacia neurophylla*)	Rock sheoak (*Allocasuarina huegeliana*), jam wattle (*Acacia acuminata*)	Salmon gum (*Eucalyptus salmonophloia*), gimlet (*E. salubris*), samphire (*Halosarcia* spp.)
Relative production levels	Typically higher for lupin, clover, wheat (except on wodjil sands)		Barley better than wheat in sodic soils Longer cereal phases Highest cereal yield potential in wet years
Major management differences	More fertiliser, often phosphate deficient, wet seeding (erosion risk)		More frequent fallowing, early seeding, difficult land preparation

[#] This nomencalture 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 3 h) 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.

Questions asked and corresponding variables	*Unit*[c]	*Number of observations*	*Inclusion in statistical analysis:*		
			tests on medians	*linear models*[d]	*mixed models*[d]
1. Land					
Farm location (3 landscape zones)	n.a.	34		EF_1	EF_1
Typical annual rainfall	mm	27		E	E
Farm area	ha	36		E	E
Non-arable area	ha	36	one-way	E	E
Arable areas typically under wheat, barley, canola, legume crops, fallow, volunteer pastures, legume pasture and permanent pasture (not rotated)	ha	36		E/D	E
Farm production orientation (2 farm types)	n.a.	36		EF_2	EF_2
Rocky arable area	ha	35	one-way	E	E
Soil types present on farm (3 major soil types)[b]	n.a.	36			EF_3
Soil types, proportion of farm arable area	%	35	one-way	E	E
Typical rotation on each soil type[b]	n.a.	83 (33 farms)			
Seeding priority criteria	n.a.	23			
Other management differences between soil types	n.a.	23			
2. Grain yields					
Typical farm grain yields (wheat, barley, canola, lupin)	t/ha	31, 17, 16, 15	one-way	D	E
Differences in typical wheat yield across soil types	t/ha	32	one-way		
Typical high and low farm wheat yields	t/ha	22	one-way		
Other performance differences between soil types	n.a.	20			
3. Grain marketing[a] **4. Sheep system**[a] **5. Farm history**[a]					
Date current manager started farming	date	36		E	
6. Workforce[a]					
Permanent labour, family and employed	FTE			E	
Casual labour employed at seeding	FTE			E	
7. Calendar of operations[a]					
Start of seeding	date	33		E/D	
End of seeding	date	33		E/D	
8. Machinery and buildings[a]					
Duration of seeding shift	hours	30		E	
9. Inputs and expenses[a]					
Wheat fertilisers (P total, N total, upfront, top-up)	units/ha	26, 28, 25, 24		E	
Consultants (agronomists and farm advisors)	k$ paid/yr	31		E	
10. Banking, challenges and plans[a]					
Equity level	ranked 1–5	28		E/D	
Calculated variables deduced from above data					
Rotation duration[b]	year	83			D
Rotation composition[b] in wheat, barley, canola, lupin and other legume crops, legume pasture, volunteer pasture or chemical fallow	%	83			D
Farm arable area under cereals	%	36		E/D	E
Farm rable area under break crops (canola, lupin, sown fodders, legume pastures)	%	36		E/D	E
Arable area per full-time workers	ha/worker	36		E	E
Seeded area per worker present at seeding	ha/worker	35		E	E
Proportion of casuals workforce present at seeding	%	36		E	
Proportion of family workforce who started before 1985 and is actively and engaged in farm decisions	%	36		E	
Enterprise diversity index[e]	%	36		E	

[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: $D_i = a + EF_{1i} + EF_{2i} + bE_{1i} + \ldots + zE_{ni}$; Mixed models: $D_{ij} = a + EF_{1i} + EF_{2i} + EF_{3ij} + bE_{1i} + \ldots + zE_{ni} + \varepsilon_i$; where i relate to farmers, j to soil types, n to the number of continuous explanatory variables included, and ε to random error terms.
[e] Adapted from Lawes and Kingwell (2012) Simpson diversity index $D = 1 - \Sigma_i p_i^2$ where p_i is the proportion of farm area typically under enterprise i (number of enterprises: 8).

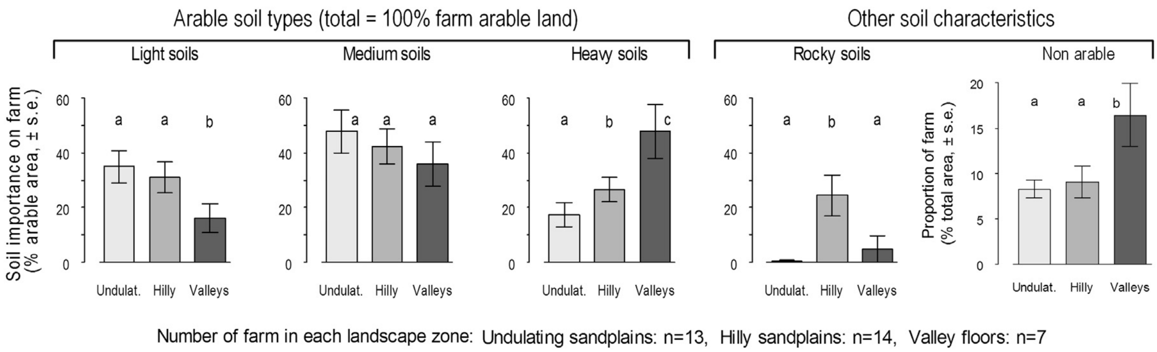

Fig. 4. Farm soil composition according to farm location (landscape zone).
Similar letters indicate no significantly different medians (p > 0.05). Rocky soils may overlap any arable soil types.

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:

$$YW_i = 1.54 + 0.66LS_i + 0.01BC_i$$

$$YC_i = 0.96 - 0.54HS_i - 0.31RS_i$$

where YW and YC are the typical farm wheat and canola yields, LS, HS and RS 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:

$$R_{ij} = a + S_j + F_i + F_i.S_j + \varepsilon_i \text{ or } R_{ij} = a + S_j + F_i + \varepsilon_i$$

where R is the rotation variable (duration, compositions), F the effect of the farm type i, S the effect of the soil type j, and ε 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 synthetised 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.

Dependent variables: typical farm yield (t/ha)	*Full model adj.R^2*	*Intercept*	*Explanatory variables[a] retained: proportion of farm arable area (%) under[b]:*			
			Light soils	*Heavy soils[c]*	Rocky soils	*Break crops[d]*
Wheat n = 30	0.60 (<0.001)	1.54 ± 0.08 (<0.001)	0.007 ± 0.001 (<0.001)	n.a.	n.a.	0.014 ± 0.003 (<0.001)
Canola n = 17	0.55 (0.001)	1.18 ± 0.05 (<0.001)	n.a.	−0.005 ± 0.001 (0.003)	−0.003 ± 0.001 (0.005)	n.t.

[a] For the full list of 36 variables included, see Table 4.
[b] Coefficient ± 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, sown fodders (e.g. oaten hay), legume pastures.

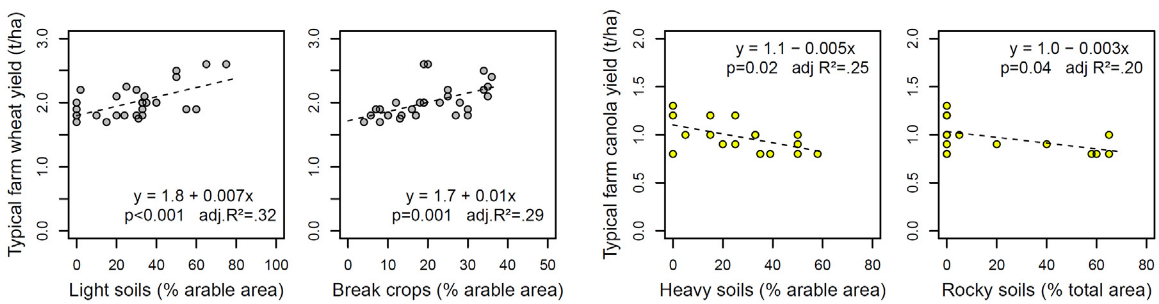

Fig. 5. Linear relationships between farm grain yields and farm characteristics (partial models).
Dashed lines represent predicted values of the positive effects of light soils and farm break crop area on wheat yields, and the negative effects of heavy and rocky soils on canola yields. The summed R^2 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 Harries 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, Galloway, 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

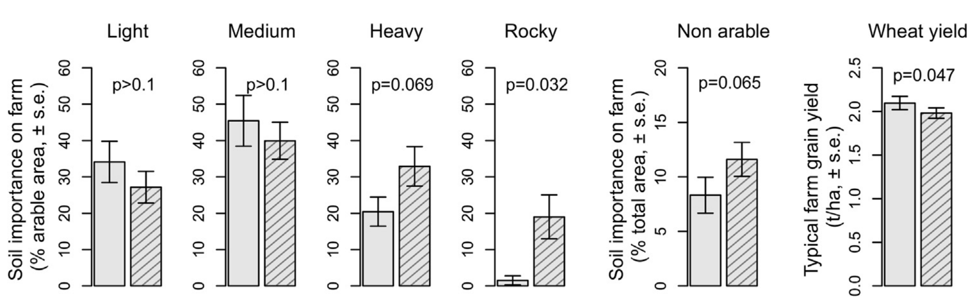

Fig. 6. Proportions of soil types, other soil characteristics and typical wheat yields between farm types.
p-values relate to differences in medians between cropping specialists who not maintain any pasture on arable land (plain bars, n_{soils} = 16, n_{yields} = 12) and mixed crop-sheep farmers (dashed bars, n_{soils} = 19, n_{yields} = 20).

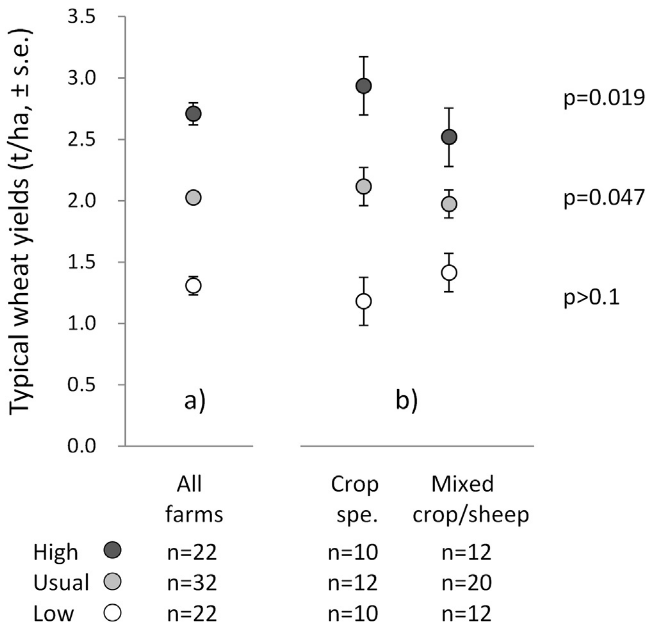

Fig. 7. Typical farm wheat yields.
Typical high, usual and low yields a) across all farms; b) according to farm type, with tests on medians under the assumption that cropping specialists have higher yields than mixed farmers. The average yield range (between high and low yields) for cropping specialists and mixed farmers significantly differs and is, respectively: 1.76 ± 0.14 and 1.10 ± 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 (Altieri 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 R^2 = 55%, wheat R^2 = 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
Latest rotation information available for the centre of the Western Australia wheatbelt.

Studies	*This study*	Harries et al. (2015)
Size of study area	4 000 km^2	approx. 12 000 km^2
Data	83 typical rotations from 36 farms	65 fields information across 4 years
Data collection procedure	Farmer interviews, 2014 (approx. 2 months)	Yearly monitoring, 2010–2014
Overall proportion of rotations[#] under each enterprise		
Cereal (Wheat + Barley)	64 (50 + 14)	66 (58 + 8)
Canola	12	12
Legumes (Lupin + Peas)	8 (7 + 1)	<7 (5 + 1)
Pastures	14	13
Fallow	<2	<1
Others	<1	<3

[#] Slight differences with farm arable 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.

Rotation variables[#]	*Soil type (Heavy, Medium, Light)*	*Farm type (Cropping specialist, Mixed)*	*Interaction*
Duration of rotation (year)	n.s.	*	***
Composition of rotation (%)			
Total cereals	n.s.	•	**
Wheat	n.s.	n.s.	n.s.
Barley	n.s.	n.s.	*
Total break crops	***	***	•
Canola	**	***	n.s.
Lupin	***	n.s.	n.s.
Total non-cropping	***	***	**
Pastures	***	n.a.	n.a
Chemical fallow	n.s.	n.a.	n.a.

[#]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 water 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., 2015; 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), Culas (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. Culas, 2011; Moore et al., 2011; Kragt 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

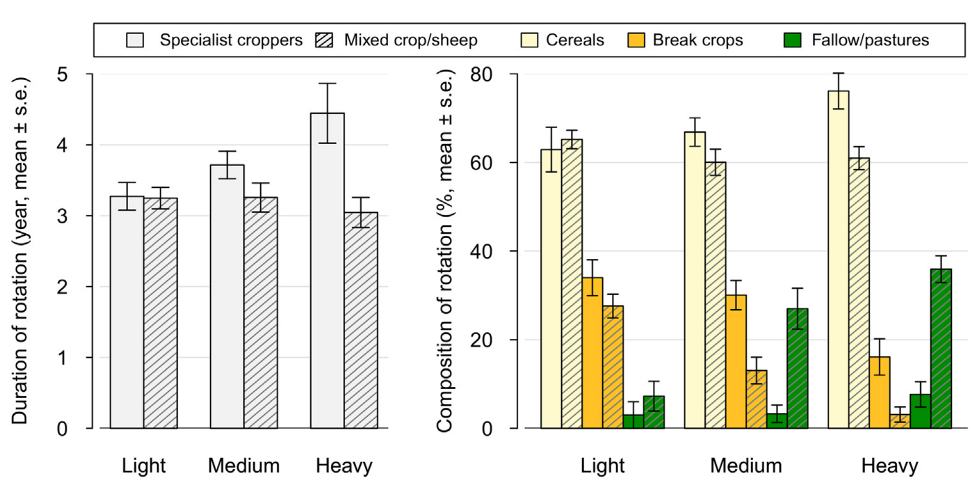

Fig. 8. Duration and composition of rotations typically conducted in the study area.
Farms included: 33 (42% cropping specialists, 58% mixed farmers). Typical rotations identified: 83, each implemented over at least 10% of the farm arable area.

Table 8
Synthesis of landscape and management heterogeneity: soil types and rotation strategies.

	Dominant soil types			*% arable in study area*
	Light	Medium	Heavy	
Average rotations				
Cropping specialists	CC(C)B	CC(C)B	CCC(C/X)B	40
Mixed crop/sheep	CC(C)B	CC(B)P	CCP	60
Zones composition (%)				
Undulating sandplains	35	45	20	50
Hilly sandplains	35	40	25	25
Valley floors	15	35	50	25
% arable in study area	30	40	30	100

See map Fig. 3 for the localisation of the zones in the landscape. Percentages are approximate. Arable area = ~90%. Rotations: C = Cereals (~80% wheat, 20% barley), B = Break crops (~60% canola, 40% lupin), P = Pastures (mainly volunteers), X = chemical fallows. For instance, CC(C)B is equivalent to "2–3 cereals followed by a break crop", with cereals sown 2.5 years out of 3.5 and thus representing approx. 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 Kirkegaard 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.) (McGuckian 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 LUSO 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 89% 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 U.S., particularly equalitarian (Lindsay, 1957; Coles, 1969; Rance, 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 advancements (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; Altieri 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; Kragt 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; McGuckian and Rickards, 2011; Deininger and Byerlee, 2012). Alternatively, the synthesis map produced can 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 breath 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 higher long-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 farm 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 McNee 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.

Appendix Supplementary data

Supplementary data (Google Maps satellite imagery) associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.plantsci.2004.08.011.

References

ABARES, 2014. Agricultural Commodity Statistics 2014. ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences), Canberra.
Alexandra, J., 2012. Australia's landscapes in a changing climate—caution, hope, inspiration, and transformation. Crop Pasture Sci. 63, 215.
Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. Agron. Sustain. Dev. 35, 869–890.
Angus, J.F., Kirkegaard, J.A., Hunt, J.R., Ryan, M.H., Ohlander, L., Peoples, M.B., 2015. Break crops and rotations for wheat. Crop Pasture Sci. 66, 523.
Appleyard, R., Couper, D., 2009. A History of Trayning. UWA Publishing, Crawley, Perth.
Aubron, C., Noël, L., Lasseur, J., 2016. Labor as a driver of changes in herd feeding patterns: Evidence from a diachronic approach in Mediterranean France and lessons for agroecology. Ecol. Econ. 127, 68–79.
Asseng, S., Dray, A., Perez, P., Su, X., 2010. Rainfall–human–spatial interactions in a salinity-prone agricultural region of the Western Australian wheat-belt. Ecol. Model. 221, 812–824.
BOM, 2015. Climate data online, monthly rainfall for the sites of Cowcowing, Ygnattering, Yorkrakine, Quondong, Trayning, Nanyanine, Bungulla (2000–2013). Australian Bureau of Meteorology. http://www.bom.gov.au Accessed: 3 Aug 2015. Bureau of Meteorology, Melbourne.
Barnaud, C., Trébuil, G., Dumrongrojwatthana, P., Marie, J., 2008. Area study prior to companion modelling to integrate multiple interests in upper watershed management of northern Thailand. SE. Asian Stud. 45, 559–585.
Barral, S., Touzard, I., Ferraton, N., Rasse-Mercat, E., Pillot, D., 2012. Assessing Smallholder Farming: Diagnostic Analysis of Family-based Agricultural Systems in a Small Region. SEARCA, Los Baños.
Bell, L.W., Moore, A.D., 2012. Integrated crop-livestock systems in Australian agriculture: trends, drivers and implications. Agric. Syst. 111, 1–12.
Cochet, H., 2012. The 'systeme agraire' concept in francophone peasant studies. Geoforum 43, 128–136.
Cochet, H., 2015. Comparative Agriculture. Springer, Netherlands, Dordrecht.
Coles, J., 1969. Memoirs of James Coles. Community Resources Centre, Kellerberrin.
Council of Europe, 2005. High-level Pan-European Conference on Agriculture and Biodiversity: Paris (France), 5–7 June 2002: Compendium of Background Reports. Council of Europe Publishing, Strasbourg.
Culas, R.J., 2011. Area response in wheat production: the Australian wheat-sheep zone. AFBM J. 8, 43–50.
DAFWA (2014). Evolution of drought policy in Western Australia. Perth: Department of Agriculture and Food Western Australia, Rural Business Development Unit.
Dale, V.H., Kline, K.L., Kaffka, S.R., Langeveld, J.W.A., 2012. A landscape perspective on sustainability of agricultural systems. Landsc. Ecol. 28, 1111–1123.
Deininger, K., Byerlee, D., 2012. The rise of large farms in land abundant countries: do they have a future? World Dev. 40, 701–714.
Doncon, G., 2014. Property Areas >10 ha, Cunderdin-Trayning, Cadastral Map 1:150 000, (2013 Fourteenth Update). Department of Agriculture and Food, Western Australia, Merredin.
Finlayson, J.D., Lawes, R.A., Metcalf, T., Robertson, M.J., Ferris, D., Ewing, M.A., 2012. A bio-economic evaluation of the profitability of adopting subtropical grasses and pasture-cropping on crop–livestock farms. Agric. Syst. 106, 102–112.
Fisher, J., Tozer, P., Abrecht, D., 2010. Review of Livestock Impacts on No-till Systems. Technical Report for GRDC. Curtin University of Technology, Muresk, School of Agriculture and Environment, Northam.
Foyer, C.H., Lam, H.-M., Nguyen, H.T., Siddique, K.H.M., Varshney, R.K., Colmer, T.D., Cowling, W., Bramley, H., Mori, T.A., Hodgson, J.M., Cooper, J.W., Miller, A.J., Kunert, K., Vorster, J., Cullis, C., Ozga, J.A., Wahlqvist, M.L., Liang, Y., Shou, H., Shi, K., Yu, J., Fodor, N., Kaiser, B.N., Wong, F.-L., Valliyodan, B., Considine, M.J., 2016. Neglecting legumes has compromised human health and sustainable food production. Nat. Plants 2, 16112.
Galloway, P., 2004. Agricultural Sub-Regions of the Avon River Basin. Resource Management Technical Report 284. Department of Agriculture and Food, Western Australia, Perth.
Geoscience Australia, 1970a. Dowerin 2335 W.A., Topographic Maps 1:100,000, 1st edition Department of Minerals and Energy, Perth.
Geoscience Australia, 1970b. Kellerberrin 2434 W.A., Topographic Maps 1:100 000, 1st edition Department of Minerals and Energy.
Google Earth. https://maps.google.com.au Accessed April 2014.
Grealish, G.J., Wagnon, J., 1995. Soil Landscape Map of the Bencubbin Region. Scale 1:100 000. Department of Agriculture and Food, Western Australia, Perth.
Handy, J., 2009. 'Almost idiotic wretchedness': a long history of blaming peasants. J. Peasant Stud. 36, 325–344.
Harries, M., Anderson, G.C., Hüberli, D., 2015. Crop sequences in Western Australia: what are they and are they sustainable? Findings of a four-year survey. Crop Pasture Sci. 66, 634.
Hochman, Z., Holzworth, D., Hunt, J.R., 2009. Potential to improve on-farm wheat yield and WUE in Australia. Crop Pasture Sci. 60, 708–716.
Hochman, Z., Gobbett, D., Holzworth, D., McClelland, T., van Rees, H., Marinoni, O., Garcia, J.N., Horan, H., 2012. Quantifying yield gaps in rainfed cropping systems: a case study of wheat in Australia. Field Crops Res. 136, 85–896.
Hogan, A., Scarr, E., Lockie, S., Chant, B., Alston, S., 2012. Ruptured identity of male farmers: subjective crisis and the risk of suicide. J. Rural Soc. Sci. 27, 118–140.
Hooper, S., Levantis, C., Formosa, T., 2011. Physical and financial performance benchmarks for grain producing farms, Western Australian central agroecological zone Report prepared for the Grains Research and Development Corporation. ABARES Canberra.
House, A.P.N., MacLeod, N.D., Cullen, B., Whitbread, A.M., Brown, S.D., McIvor, J.G., 2008. Integrating production and natural resource management on mixed farms in eastern Australia: the cost of conservation in agricultural landscapes. Agric. Ecosyst. Environ. 127, 153–165.
Hughes, N., Lawson, K., Davidson, A., Jackson, T., Sheng, Y., 2011. Productivity Pathways: Climate Adjusted Production Frontiers for the Australian Broadacre Cropping Industry. Research Report 11.5. ABARES, Canberra.
Kingwell, R., Anderton, L., Islam, N., Xayavong, V., Wardell-Johnson, A., Feldman, D., Speijers, J., 2013. Broadacre Farmers Adapting to a Changing Climate. National Climate Change Adaptation Research Facility, Gold Coast.
Kirkegaard, J.A., Peoples, M.B., Angus, J.F., Unkovich, M.J., 2011. Diversity and evolution of rainfed farming systems in southern Australia. In: Tow, P., et al. (Ed.), Rainfed Farming Systems. Springer, Netherlands, Dordrecht, pp. 715–754.
Kragt, M.E., Pannell, D.J., Robertson, M.J., Thamo, T., 2012. Assessing costs of soil carbon sequestration by crop-livestock farmers in Western Australia. Agric. Syst. 112, 27–37.
Lacoste, M., Lawes, R., Ducourtieux, O., Flower, K., in press Methods to Study Agricultural Systems (accepted 9 Aug 2016). In: Lichtfouse, E. (Ed.), Sustainable Agriculture Reviews. Springer International Publishing, Cham.
Lantzke, N., Fulton, I., 1992. Soil Landscape Map of the Northam Region. Scale 1:100 000, Land Resource Map No. 11/1. Department of Agriculture, Western Australia, Perth.
Lantzke, N., Fulton, I., 1993. Land Resources of the Northam Region. Land Resources Series No.11. Department of Agriculture and Food, Western Australia, Perth.
Lawes, R.A., Kingwell, R.S., 2012. A longitudinal examination of business performance indicators for drought-affected farms. Agric. Syst. 106, 94–101.
Lawes, R., Renton, M., 2015. Gaining insight into the risks, returns and value of perfect knowledge for crop sequences by comparing optimal sequences with those proposed by agronomists. Crop Pasture Sci. 66, 622.
Lawes, R., van Der Zee, C., 2015. Planning horizon, commodity price and weed burden influence the number of break crops in a crop sequence. Proceedings of the 17th Australian Society of Agronomy Conference, 20–24 September 2015, Hobart, Australia.
Lawes, R.A., Oliver, Y.M., Robertson, M.J., 2009. Integrating the effects of climate and plant available soil water holding capacity on wheat yield. Field Crops Res. 113, 297–305.
Lawes, R., 2010. Using industry information to obtain insight into the use of crop rotations in the Western Australian wheat belt and quantifying their effect on wheat yields. Proceedings of the 15th Australian Agronomy Conference, 15–18 November 2010, Lincoln, New Zealand.
Lawes, R., 2015a. How risky is your rotation? Proceedings of the 2015 Agribusiness Crop Updates, 24–25 February, Perth, Australia.
Lawes, R.A., 2015b. Crop sequences in modern Australian farming systems. Crop Pasture Sci. 66, i–ii.
Le Gal, P.Y., Dugué, P., Faure, G., Novak, S., 2011. How does research address the design of innovative agricultural production systems at the farm level? A review. Agric. Syst. 104, 714–728.
Lefroy, E.C., Hobbs, R.J., Atkins, L.J., 1991. Revegetation Guide to the Central Wheatbelt. Bulletin 4231. Department of Agriculture, Western Australia, Perth.
Lindsay, J., 1957. Hon. John Lindsay's Reminiscences Regarding Wyalcatchem. CBH Agricultural Museum, Wyalkatchem.
Lyle, G., 2015. Understanding the nested, multi-scale, spatial and hierarchical nature of future climate change adaptation decision making in agricultural regions: a narrative literature review. J. Rural Stud. 37, 38–49.
Martin, G., Martin-Clouaire, R., Duru, M., 2012. Farming system design to feed the changing world. A review. Agron. Sustain. Dev. 33, 131–149.
Mazoyer, M., Roudart, L., 2007. A History of World Agriculture: from the Neolithic Age to the Current Crisis. Earthscan Routledge, London.
McArthur, W.M., 1992. Soil Landscape Map of the Kellerberrin Region. Scale 1:100 000. Department of Agriculture and Food, Western Australia, Perth.
McBeath, T.M., Gupta, V.V.S.R., Llewellyn, R.S., Davoren, C.W., Whitbread, A.M., 2015. Break-crop effects on wheat production across soils and seasons in a semi-arid environment. Crop Pasture Sci. 66, 566.
McGuckian, N., Rickards, L., 2011. The social dimensions of mixed farming systems. In: Tow, P., et al. (Ed.), Rainfed Farming Systems. Springer, Netherlands, Dordrecht, pp. 805–821.
Moore, A.D., Robertson, M.J., Routley, R., 2011. Evaluation of the water use efficiency of alternative farm practices at a range of spatial and temporal scales: a conceptual framework and a modelling approach. Agric. Syst. 104, 162–174.
Moreau, P., Ruiz, L., Mabon, F., Raimbault, T., Durand, P., Delaby, L., Devienne, S., Vertès, F., 2012. Reconciling technical, economic and environmental efficiency of farming systems in vulnerable areas. Agric. Ecosyst. Environ. 147, 89–99.
Mulhling, P.C., Thom, R., 1985. Kellerberrin SH 50-15. Geological Series 1:250 000. Department of Minerals and Energy, Perth 1st Edition (geology: 1979).
O'Byrne, D., 2009. South West WA, Altlas and Guide. Scale 1:250 000, 2nd edition Hema Maps, Brisbane.

Oliver, Y.M., Robertson, M., Stone, P.J., Whitbread, A.M., 2009. Improving estimates of water-limited yield of wheat by accounting for soil type and within-season rainfall. Crop Pasture Sci.
Oliver, Y.M., Robertson, M.J., Weeks, C., 2010. A new look at an old practice: benefits from soil water accumulation in long fallows under Mediterranean conditions. Agric. Water Manag. 98, 291–300.
Philip Robertson, G., Gross, K.L., Hamilton, S.K., Landis, D.A., Schmidt, T.M., Snapp, S. S., Swinton, S.M., 2014. Farming for ecosystem services: an ecological approach to production agriculture. Bioscience 64, 404–415.
Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., R Core Team, 2015. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3. 1–121. CRAN.R-project. org/package=nlme.
Price, J.C., Leviston, Z., 2014. Predicting pro-environmental agricultural practices: the social, psychological and contextual influences on land management. J. Rural Stud. 34, 65–78.
R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. www.R-project.org.
Rance, J.A., 2005. Reminiscences. Bayswater, Trayning.
Robertson, M.J., Kingwell, R., Measham, T.G., O'Connor, M., Batchelor, G., 2009. Constraints to farmers managing dryland salinity in the central wheatbelt of Western Australia. Land Degrad. Dev. 20, 235–251.
Robertson, M.J., Lawes, R.A., Bathgate, A., Byrne, F., White, P., Sands, R., 2010. Determinants of the proportion of break crops on Western Australian broadacre farms. Crop Pasture Sci. 61, 203–213.
Robertson, M.J., Llewellyn, R.S., Mandel, R., Lawes, R., Bramley, R.G.V., Swift, L., Metz, N., O'Callaghan, C., 2012. Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects. Precis. Agric. 13, 181–199.
Rodriguez, D., Cox, H., deVoil, P., Power, B., 2014. A participatory whole farm modelling approach to understand impacts and increase preparedness to climate change in Australia. Agric. Syst. 126, 50–61.
Ruisi, P., Saia, S., Badagliacca, G., Amato, G., Frenda, A.S., Giambalvo, D., Di Miceli, G., 2016. Long-term effects of no tillage treatment on soil N availability N uptake, and 15N-fertilizer recovery of durum wheat differ in relation to crop sequence. Field Crops Res. 189, 51–58.
Sawkins, D., 2010. Landscapes and Soils of the Northam District. Bulletin 4803. Department of Agriculture and Food, Western Australia, Northam.
Schoknecht, N., Pathan, S., 2013. Soil Groups of Western Australia. A Simple Guide to the Main Soils of Western Australia. Resource Management Technical Report 380, 4th edition Department of Agriculture and Food, Western Australia, Perth.
Seymour, M., Kirkegaard, J.A., Peoples, M.B., White, P.F., French, R.J., 2012. Break-crop benefits to wheat in Western Australia—insights from over three decades of research. Crop Pasture Sci. 63, 1–16.
Shanks, T.R.W., 2005. The homestead act of the nineteenth century and its influence on rural lands. CSD Working Papers, Wealth Building in Rural America Project Washington: Center for Social Development. Washington University.
Sutherland, L.-A., Burton, R.J.F., Ingram, J., Blackstock, K., Slee, B., Gotts, N., 2012. Triggering change: towards a conceptualisation of major change processes in farm decision-making. J. Environ. Manag. 104, 142–151.
Thompson, T., 2015. Australian Grains: Financial Performance of Grain Producing Farms, 2012–13 to 2014–15. Report for the Grains Research and Development Corporation. ABARES, Canberra.
Verboom, W.H., Pate, J.S., 2003. Relationships between cluster root-bearing taxa and laterite across landscapes in southwest Western Australia: an approach using airborne radiometric and digital elevation models. Plant Soil 248, 1–2.
Verboom, W.H., Pate, J.S., 2013. Exploring the biological dimension to pedogenesis with emphasis on the ecosystems, soils and landscapes of southwestern Australia. Geoderma 211–212, 154–183.
Villano, R., Fleming, E., Fleming, P., 2010. Evidence of farm-level synergies in mixed-farming systems in the Australian Wheat-Sheep Zone. Agric. Syst. 103, 146–152.
Wolfe, E.C., 2011. Interactions between crop and livestock activities in rainfed farming systems. In: Tow, P., et al. (Ed.), Rainfed Farming Systems. Springer, Netherlands, Dordrecht, pp. 271–298.
van Gool, D., Vernon, L., Runge, W., 2008. Land Resources in the South-West Agricultural Region. A Shire-based Summary of Land Degradation and Land Capability. Resource Management Technical Report 330. Department of Agriculture and Food, Western Australia, Perth.
van Rees, H., McClelland, T., Hochman, Z., Carberry, P., Hunt, J., Huth, N., Holzworth, D., 2014. Leading farmers in South East Australia have closed the exploitable wheat yield gap: prospects for further improvement. Field Crops Res. 164, 1–11.