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A NEW DRYLAND DEVELOPMENT PARADIGM GROUNDED IN EMPIRICAL ANALYSIS OF DRYLAND SYSTEMS SCIENCE

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ABSTRACT

Global drylands face a host of urgent human and environmental challenges with far-reaching impacts. Improving smallholder agriculture remains a key development pathway to tackle these challenges. The dryland development paradigm (DDP), introduced in 2007, presented a highly influential framework for dryland development based on systems research. This paper empirically derives a new, updated DDP. It assesses recent, cutting-edge dryland science, combining literature review with qualitative and quantitative analysis of research published by the world's largest dryland science and development research initiative. The new DDP comprises eight characteristics that are distilled into three integrative principles: *Unpack*, *Traverse* and *Share*. The new DDP is applied and tested to identify key dryland knowledge and development gaps. A future research agenda is then elucidated, grounded in a research in development approach, in which research anchored in the three integrative principles is embedded within the context it seeks to improve. Supported by greater trans-disciplinarity and knowledge co-production, operationalization of the new DDP can deliver both novel scientific insights and development impact in line with the aspirations of the 2030 Sustainable Development Goals. © 2017 The Authors. Land Degradation & Development Published by John Wiley & Sons Ltd.

KEY WORDS: agricultural systems; livelihoods; arid and semi-arid environments; social-ecological resilience; sustainable development goals

INTRODUCTION

Drylands occupy 41% of the global land surface (Reynolds *et al.*, 2007) and are inhabited by more than 2.5 billion of the poorest, hungriest, least healthy and most marginalized people in the world (Middleton *et al.*, 2011). Dryland agricultural livelihoods are being undermined by converging factors including poverty and unemployment related to high population growth rates, weak governance, low inherent agricultural productivity, low levels of investment and land degradation (Reed & Stringer, 2016). Climate change, conflict and civil unrest impose additional pressures on scarce resources in vulnerable drylands and exacerbate human migration (Okpara *et al.*, 2015, 2016a). Despite their problems, drylands also possess valuable assets, e.g. abundant solar energy, rich plant biodiversity, 50% of the world's livestock and opportunities to diversify and intensify agriculture and increase soil carbon storage (Mortimore *et al.*, 2009; Stringer *et al.*, 2012). Overall, these challenges and opportunities combine to create a major scientific and international development task: identifying pathways towards dryland agricultural development that both harness the strengths and complexity of these areas and tackle

their problems in a timely, cost-effective way. The economic and human costs of inaction or delayed action in addressing dryland problems are likely to be substantial (ELD, 2015), while failure to substantially address the challenges posed by these environments will stall progress towards achieving international development goals (Mortimore *et al.*, 2009). Indeed, slow movement towards the Millennium Development Goals (MDGs) is testament to this (Middleton *et al.*, 2011).

Dryland development efforts have been spearheaded by a range of international actors and agencies for several decades: historically, by investing in large-scale, top-down agricultural interventions, devised to control or manage biophysical processes (Toulmin & Brock, 2016); more recently, through the development and application of systems approaches and research for development (Reynolds & Stafford-Smith, 2002; Reynolds *et al.*, 2007). Herein, the agricultural sector has received significant attention. Smallholder agriculture remains the main driver of development in developing countries and is central to food security, generating employment and contributing a significant percentage of Gross Domestic Product in many drylands (Mortimore *et al.*, 2009). Improving the benefits from and profitability of smallholder farming remains an urgent task for dryland communities where livelihoods are characterized by risks and complexities associated with water scarcity, climatic variability, land degradation and the governance

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and social systems that have developed to cope with uncertainty (UNEMG, 2011). Dryland development also remains a key priority for international actors and agencies which recognize that the future pathways taken by the drylands have multiple knock-on global impacts.

The aim of this paper is to provide an empirically grounded assessment of the state-of-the-art in dryland science and development, informing the identification and application of a new, forward-looking dryland development paradigm (DDP), and a research agenda that can help to address the key dryland challenges identified above. We first assess the current state of dryland research, highlighting the importance of Reynolds *et al.*'s (2007) DDP and illustrating its use by the dryland science community. From this, we take stock and empirically establish eight key characteristics of a new DDP that capture the evolution of drylands research as presented within the literature. Synthesizing these eight characteristics as the current cutting-edge, we identify a simple set of three integrative principles that operationalize the new DDP. We apply the integrative principles to research undertaken by the CGIAR Research Programme on Dryland Systems (CRP-DS),¹ assessing the current strengths and gaps in dryland science and development in the largest international drylands research initiative in the world. Application of the three integrative principles allows the derivation of future research steps that can more holistically advance knowledge and address dryland development challenges. Viewed together, the new DDP's integrative principles can be used by researchers and donors to identify whether urgent dryland knowledge and development impact gaps are being sufficiently addressed. This is particularly important in the design of interventions seeking to advance progress towards the 2030 Sustainable Development Goals (SDGs) in drylands.

RESEARCH DESIGN AND METHODOLOGY

Our research design combined literature review with qualitative and quantitative analysis of CRP-DS documents in a three-step process, allowing correlations between different parts of the DDP and synthesis of context-specific studies from the CRP-DS with broader approaches from the literature.

¹The CGIAR is the world's largest group of researchers working on advancing agricultural development and innovation. Focusing on this body of work provides a unique opportunity to explore the implications of a modern, systems-based approach to dryland development in agricultural systems around the world. Its efforts explicitly target the poor by linking scientific research with development impact, through system level outcomes focused on reducing poverty, enhancing food and nutrition security for health and improving natural resource systems and ecosystem services. Climate change, gender, youth, policies, institutions and capacity development are treated as cross-cutting issues. The Dryland Systems Research Programme involves eight CGIAR research centres, as well as external partnerships (CGIAR, 2014; 2015). Its research focuses on a broad range of dryland land use systems (pastoral, agro-pastoral, rainfed, tree-based and irrigated) and has sought to move away from conventional approaches towards the development and application of systems thinking (CGIAR, 2014).

Step 1: Literature Review

A literature review was undertaken to identify dominant dryland research and development characteristics since the turn of the century using Google, Google Scholar and Web of Knowledge, as well as analysing academic and grey literature publications within the CRP-DS's Monitoring, Evaluation and Learning platform.² The year 2000 was set as a baseline for our sample because it was the beginning of the MDGs (precursor to the SDGs) which were paramount in guiding international development interventions in drylands (and elsewhere) up to 2015. Initial findings highlighted the Reynolds *et al.*'s (2007) DDP as a key milestone in dryland science and development research. The year 2000 baseline allowed us to view Reynolds *et al.*'s (2007) work in the context of the literature it synthesized and built upon (in particular, Reynolds & Stafford-Smith, 2002; Stafford-Smith & Reynolds, 2002). Eight characteristics of a new DDP were compiled based on evidence of approaches to dryland science and development emerging from the literature review. Comparing the historical approaches critiqued in the literature, our eight characteristics and the principles of Reynolds *et al.*'s (2007) DDP allowed us to synthesize three integrative principles. These provide a minimum set of components for future research and impact in a new DDP.

To test the three integrative principles, we applied the new DDP using quantitative and qualitative methods in steps 2 and 3 to understand how they had been applied in the CRP-DS and to enable identification of particular strengths, gaps and relationships between the integrative principles in the regions and livelihood systems of their application. We considered all 68 peer-reviewed journal papers reported in the CRP-DS annual reports from 2014 and 2015. This body of literature explicitly followed a modern, systems-based approach that extended the DDP (Van Ginkel *et al.*, 2013). All of these papers were published by authors funded by the CRP-DS during the period 2012–2016.

Step 2: Quantitative Analysis

Quantitative analysis started with stripping author affiliations, acknowledgements and references from article full texts. RapidMiner Studio 7.2 software (one of the most commonly used open-source data mining tools) was used as a tool to create word lists from the remaining article text. Words occurring in <7 (~10%) papers were omitted from the analysis. Texts were also stripped of non-letter symbols, cases were transformed and stop words (e.g. 'the', 'is', 'at', 'which') were excluded (Leskovec *et al.*, 2014). To account for compound words with specific meanings (e.g. 'production systems'), all combinations of up to three words were maintained if passing the ~10% minimum threshold. This resulted in 3,449 different words and word combinations. From this list, words occurring ≥ 50 times in the total sample of papers were selected to create a longlist of 990 words.

²<http://mel.cgiar.org/xmlui/handle/20.500.11766/1>

From the longlist, a shortlist of words that could be associated with characteristics identified in the literature review was elucidated by one author and independently checked by a second author. This resulted in 208 words categorized under the eight characteristics and three integrative principles (Table S1).

All authors plus another expert from the CRP-DS ($n = 7$ experts) participated in an expert panel, in which we evaluated the relevance of each word in relation to the principle under which it had been categorized. Relevance was scored individually by each expert on a scale of 0–2 (not relevant to highly relevant). Scores were summed to give each word a weight of between 1 and 14, with words scoring zero removed from the analysis. Through discussion, some words were re-categorized under a different, more relevant principle, and re-scored in relation to the new principle. Sums of representative word counts were made per characteristic and analysed as a total set, per region and per dryland agricultural (livelihood) system covered by the CRP-DS. This allowed assessment of the frequencies at which each characteristic and principle was being used and identification of any differences in their application across regions and agricultural livelihood systems. Differences between regions or agricultural livelihood systems were analysed statistically using ANOVA in SPSS Version 22. Correlations between word counts per characteristic were also made based on individual papers and assessed statistically using Pearson's correlation coefficients. Both for the regional and per-paper analysis, word counts were normalized to eliminate biases due to uneven paper length and regional sample sizes, leaving representative counts.

Step 3: Qualitative Analysis

The same sample of documents was analysed qualitatively using thematic coding under each of the three integrative principles. This enabled creation of a narrative about how each principle was being used in the CRP-DS literature and was cross-checked with the data obtained from the quantitative analysis. Finally, the expert panel identified three case studies from the CRP-DS literature that could epitomize the new DDP. This provided an in-depth illustration of how each principle had been applied in practice to deliver scientific advances and development impact.

RESULTS

Towards a New DDP

Our literature review is synthesized in Appendix S1 and demonstrates that Reynolds *et al.*'s DDP (Table I) is evidenced (explicitly and implicitly; and to varying degrees of depth) in much of the contemporary dryland research literature. Many of the papers reviewed recognize that dryland development on the scale envisaged by the MDGs (now the SDGs) requires researchers to embrace complexity, diversity and uncertainty, looking across different system components, scales and types of knowledge. They also reveal

distinctions that have emerged within the modern dryland science and development arena, with management efforts shifting away from simply combating land degradation and desertification to consider, e.g. sustainable land management and land degradation neutrality.

Reynolds *et al.*'s (2007) DDP was largely derived from an understanding of the biophysical dynamics in drylands, drawing attention to biophysical processes and interactions that had been previously under-represented in conventional approaches. While the DDP mentions the importance of understanding the roles of people in dryland systems, it does not provide concrete guidance on how social, economic, cultural, political and institutional integration and complexity can be addressed. This contrasts with other approaches that were developing in parallel in the socio-ecological systems arena (e.g. Ostrom, 2009). It also remains rather conceptual, without empirical grounding.

Our analysis revealed that more nuanced insights derived through integrated modelling, development of decision support tools and use of participatory approaches have helped to unravel complex relationships over multiple temporal and spatial scales in an iterative, interdisciplinary and inclusive way. While these approaches may have been generated in other (non-dryland) systems (see, e.g. Öborn *et al.*, 2017) and then applied to dryland settings, they push the boundaries of the DDP's call to integrate knowledges and processes, and underpin the new paradigm.

Overall, from the literature, we identified eight characteristics of modern approaches to dryland science and development which comprise a new DDP. These are contrasted with conventional approaches that do not follow any of Reynolds *et al.*'s (2007) DDP principles (Table II).

The eight characteristics in Table II can be distilled into three integrative principles that can operationalize the new DDP (Table III and Figure 1). These act as a 'minimum set' of integrative principles that cross-cut the eight characteristics, and which can serve a screening purpose for donors and research funders yet still capture dryland complexities and dynamics across multiple scales and stakeholders. They can also act as a checklist for researchers that they are using state-of-the-art approaches that build on an established empirical basis. Research typically begins with *Unpacking*, then *Traversing* and *Sharing*, and each principle supports the others.

Applying and Testing the New DDP

Quantitative analysis sought to understand the ways in, and extent to which, CRP-DS research is applying each the three integrative principles. The overall (global) sample of papers included an average representative word count that was highest for characteristics under *Unpack*, and lowest under *Share*. Word counts evidencing specific attention to inter- or trans-disciplinarity were nevertheless relatively low (Table IV). In terms of the number of papers in which each characteristic was covered, differences were less pronounced, except for the number of papers where impacts on disadvantaged groups were discussed.

Table I. Dryland development paradigm^a in 2007 (from Reynolds *et al.*, 2007: 849).

Principle	Explanation
1: Human–environment systems are coupled, dynamic and co-adapting, so that their structure, function and inter-relationships change over time.	The close dependency of most drylands livelihoods on the environment imposes a greater cost if the coupling becomes dysfunctional; variability caused by biophysical factors as well as markets and policy processes, which are generally beyond local control, means that tracking the evolving changes and their functionality is relatively harder and more important in drylands. Understanding dryland desertification and development issues always requires the simultaneous consideration of both human and ecological drivers, and the recognition that there is no static equilibrium ‘to aim for’.
2: A limited suite of ‘slow’ variables are critical determinants of human–environment system dynamics.	Identifying and monitoring the key slow human and environmental variables are particularly important in drylands because high variability in ‘fast’ variables masks fundamental change indicated by slow variables. A limited suite of critical processes and variables at any scale makes a complex problem tractable.
3: Thresholds in key slow variables define different states of human–environment systems, often with different controlling processes; thresholds may change over time.	Thresholds particularly matter in drylands because the capacity to invest in recovering from the impacts of crossing undesirable thresholds is usually lower per unit (area of land, person, etc.), and, where outside agencies must be called upon, the transaction costs of doing so to distant policy centres are usually higher. The costs of intervention rise nonlinearly with increasing land degradation or the degree of socioeconomic dysfunction; yet high variability means great uncertainty in detecting thresholds, implying that managers should invoke the precautionary principle.
4: Coupled human–environment systems are hierarchical, nested, and networked across multiple scales.	Drylands are often more distant from economic and policy centres, with weak linkages; additionally, regions with sparse populations may have qualitatively different hierarchical relationships between levels. Human–environment systems must be managed at the appropriate scale; cross-scale linkages are important in this but are often remote and weak in drylands, requiring special institutional attention.
5: The maintenance of a body of up-to-date local ecological knowledge is key to functional co-adaptation of human–environment systems.	Support for local ecological knowledge is critical in drylands because experiential learning is slower where monitoring feedback is harder to obtain (owing to more variable systems, larger management units, in sparsely populated areas) and, secondarily, where there is relatively less research. The development of appropriate hybrid scientific and local ecological knowledge must be accelerated both for local management and regional policy.

^aOverall, the Reynolds *et al.* (2007) DDP focuses on dryland natural-resource dependent livelihoods, taking a coupled human–environmental systems perspective. It takes into account research and policy trends of the era and acknowledges the links between population growth, ecosystem management and the demands people place on the environment. Although dominated by ecological processes, the DDP nevertheless draws on development thinking at the time in which it was developed by incorporating vulnerability, poverty and community development considerations.

The global findings remain valid at regional level: most attention is paid to *Unpack* and least to *Share* (Figure 2 and Table S2). Publications from East and southern Africa and West Africa showed most equal treatment of each principle. However, *Unpack* scores are relatively low in West Africa, which could point to a lack of systematic analyses of livelihood dynamics in papers sampled from this region.

Representative word counts across different dryland agricultural livelihood systems (Figure 3 and Table S3) showed scores for *Unpack* were highest when multiple agricultural systems were addressed, indicating integrative scenario studies considering synergies and trade-offs tend to be conducted at larger scales representing a variety of systems. Interactions between value chains and value chain actors were most commonly addressed in agro-pastoral systems, showing a relative difference regarding *Traverse*. Overall attention to *Share* was also highest for agro-pastoral

systems and relatively low for irrigated, rainfed and multiple systems.

Correlation analysis between characteristics revealed a central role of inter- and trans-disciplinarity with significant linkages across the three principles (Table S4). This suggests that inter- and trans-disciplinary approaches are a precondition to *Unpacking* livelihoods, *Traversing* scales and *Sharing* knowledge. Explicit consideration of trade-offs among multiple options is however negatively correlated with inter- and trans-disciplinarity, suggesting that research into trade-offs is as yet often too narrowly framed. Table S4 also highlights negative correlations between characteristics under *Unpack* and *Traverse*: research either focuses on livelihood portfolios, or on interactions between multiple drivers of change or investment options, but livelihood portfolios under multiple drivers of change are rarely assessed. Strongest and most significant correlations occur between the

Table II. Conventional approach and characteristics of a new dryland development paradigm

Conventional approach	Characteristics of a new dryland science and development paradigm
Focus on single commodities and single livelihood components without considering connections Aimed at improving productivity and closing yields gaps, regardless of risk	Focus on complex social–ecological systems and livelihood portfolios Explicit consideration of trade-offs among multiple aims—improving productivity, reducing risk and social, economic and environmental sustainability; targets multiple wins where possible; balances trade-offs where not
Focus on discrete value chains, overlooking externalities and interlinkages that can play an important role in shaping vulnerability of different value chain actors Narrow focus on innovations and investments that respond to specific drivers of change within sectors at discrete scales	Attention to interactions between value chains and how they network, explicitly considering externalities and vulnerabilities Broader focus on innovations and investments that respond to interactions between multiple drivers of change across sectors and scales
Linear, research <i>for</i> development approach where interventions are developed independent of context Mono-disciplinary (where knowledge and theory is generated in individual disciplines) or multi-disciplinary (with loose cooperation between disciplines for exchange of knowledge between disciplines, often towards end of project, to achieve a shared goal) One way ‘transfer’ of scientific knowledge to stakeholders, with emphasis on dissemination	Iterative research <i>in</i> development approach facilitating scaling up and out Interdisciplinary (where different disciplines work towards a shared goal with integration of disciplinary approaches and knowledge and development of new integrated knowledge from the outset) or trans-disciplinary (where interdisciplinary research is co-produced with stakeholders) Two-way exchange and co-production of knowledge between researchers and stakeholders, drawing on multiple knowledge sources and improving local ownership of development pathways
Gender equality and social justice are seen as outcomes of the research	Disadvantaged groups are engaged and empowered throughout the research process

characteristics of *Share*. Integration of scientific and local knowledge is strongly associated with inclusion and empowerment of disadvantaged groups (Pearson correlation coefficient 0.501, 99% confidence level) clearly evidencing that attention to local systems understandings goes together with inclusive approaches. Strong correlations between characteristics of *Share* imply that all essential dimensions of *Share* can be handled in an integrated way, and that existing research is already doing this. The challenge is to integrate these across *Unpack* and *Traverse*.

Findings at the level of characteristics hold when examining correlations at principle level (Table S5). Overall, there is a

clear lack of integrated attention to *Unpack* and *Traverse*, and a positive correlation between *Traverse* and *Share*. The regional breakdown demonstrates that *Unpack* and *Traverse* need not be incompatible: the global/continental scale papers ($n = 7$) achieve a very strong correlation of both principles (Pearson correlation coefficient 0.920, confidence level 99%). Similarly, the set of papers from South and Central Asia shows high correlation between *Traverse* and *Share* (Pearson correlation coefficient 0.760, confidence level 99%).

The qualitative analysis sought to understand how research from the CRP-DS implemented each of the three integrative principles. The results are provided in full in

Table III. Three integrative principles that can operationalize the new DDP

Principle	Explanation
<i>Unpack</i> relationships and interactions in social–ecological systems, livelihood portfolios and value chains	Drylands are coupled social–ecological systems, dynamic and co-adapting in terms of their ecology and their socio-economic portfolios, value chains and externalities. Unpacking and understanding these relationships can facilitate boundary setting and problem structuring, and allows identification of linkages and feedbacks as well as the roles and relationships between multiple actors involved in decision making.
<i>Traverse</i> scales (temporal and spatial), sectors, stakeholders and ways of knowing	Dryland development is mediated by interactions between multiple drivers of change, socio-technical innovation and investment options across sectors and scales. As complex systems, drylands operate across multiple, nested spatial scales, comprising fast and slow variables that may cross thresholds leading to non-linear dynamics and unpredictable outcomes. As such, research needs to be situated in and informed by development contexts, incorporating multiple knowledges.
<i>Share</i> knowledge, learning and experience to empower	Dryland science and development typically require inter- or trans-disciplinary approaches that combine local and scientific knowledge to co-produce outcomes for communities, which may become situated at broader spatial or social scales through social learning, including and empowering disadvantaged groups throughout the research and development process. This reinforces the need for a research <i>in</i> development approach.



Figure 1. Three integrative principles that can operationalize the new dryland development paradigm. The principles provide a checklist for researchers and an evaluation framework for funders using the new DDP. The principles suggest that dryland development research must *Unpack* relationships, *Traverse* scales and sectors and *Share* knowledge. Each principle comprises a number of characteristics, two of which (1.1 and 3.2) cross-cut two of the principles. [Colour figure can be viewed at wileyonlinelibrary.com]

Appendix S2 and summarized here under each integrative principle. Table S6 provides exemplar case studies from the CRP-DS in which the principles are operationalized together, with cases ranging from local and national to global studies, across a range of agricultural systems.

1. *Unpack*: Research frequently adopted mixed methods including in-depth qualitative fieldwork to understand livelihood portfolios as part of wider social–ecological systems. This enabled researchers to identify multiple benefits for and pressures on livelihoods arising from different parts of the system. Conceptions of dryland social–ecological systems were typically broad, considering links to the institutional environment beyond the household in order to understand

wider influences on livelihood strategies. Numerous papers considered trade-offs among multiple livelihood aims and options. Some of these studies were field-based, analysing current practices; others considered likely livelihood trade-offs and adaptations under future scenarios. Seven papers considered livelihood dependencies upon ecosystem services and two of these proposed Payment for Ecosystem Service as a way of diversifying livelihoods and reducing trade-offs.

2. *Traverse*: 21 papers sought to understand interactions between multiple drivers of change at different temporal and spatial scales, considering opportunities for innovation and adaptation. Modelling studies were able to consider the impacts of multiple interacting drivers of change from regional to global scales, aiding assessment

Table IV. Overall word counts per characteristic

Principle	Characteristic	Average representative word count (± standard deviation)	Average number of papers (± standard deviation)
<i>Unpack</i>	1.1 Focus on social–ecological systems and livelihood portfolios	199 ± 186 ^{abc}	29 ± 16
	1.2 Explicit consideration of trade-offs among multiple aims/options and other factors determining livelihood strategies	208 ± 149 ^{ab}	28 ± 16
<i>Traverse</i>	2.1 Attention to interactions between value chains and value chain actors	239 ± 264 ^a	29 ± 14
	2.2 Focus on interactions between multiple drivers of change and innovation and investment options across sectors and scales	158 ± 69 ^{bcd}	30 ± 13
<i>Share</i>	3.1 Iterative research in development approach	202 ± 64 ^{ab}	31 ± 13
	3.2 Inter- or trans-disciplinarity	113 ± 13 ^d	30 ± 9
	3.3 Local and scientific knowledge combined, co-generated and embedded in the broad community	124 ± 25 ^d	32 ± 16
	3.4 Disadvantaged groups involved and empowered throughout	139 ± 42 ^{cd}	25 ± 10

Different letters indicate statistically significant differences in word counts at 95% confidence level.

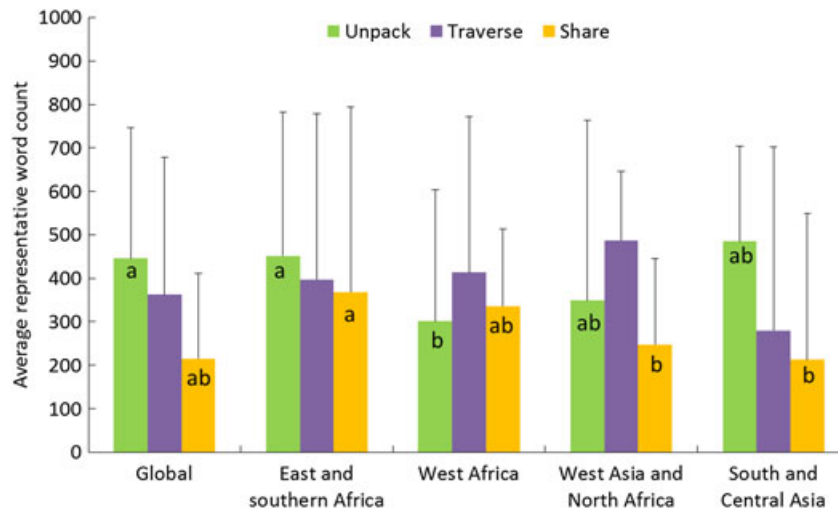


Figure 2. Regional representative word counts per principle. Bars indicate standard deviation. Different letters indicate statistically significant differences in word counts at 95% confidence level. [Colour figure can be viewed at wileyonlinelibrary.com]

of trade-offs at broad spatial scales. Rather than simply modelling biophysical processes, studies tended to model a range of social and institutional factors as part of a systems approach. Papers in the sample also sought to unravel relationships and interactions in sustainable, pro-poor value chains and between value chain actors. By looking at value chains through a systems lens, studies were able to examine broader issues such as infrastructure development and institutional reform.

3. *Share*: Although much of the research in our sample of papers was multidisciplinary and interdisciplinary, this was rarely discussed or explicitly highlighted, perhaps because it was problem focused. Nevertheless, few mono-disciplinary studies were found, and there were calls for more cross-disciplinary approaches to overcome the fragmented nature of the evidence base in many areas. Several papers sought explicitly to integrate local and scientific knowledge, or enabled researchers and stakeholder communities to co-produce knowledge. These papers took a critical and reflexive approach to co-production and participation,

highlighting challenges as well as successes. Despite the challenges, many studies placed strong emphasis on involving and empowering disadvantaged or marginalized groups.

DISCUSSION

Our analysis empirically derived a new DDP comprising eight characteristics, which were distilled into three integrative principles that operationalize the new DDP: *Unpack*, *Traverse* and *Share* (Figure 1). It provides an important contribution to the literature as it empirically articulates the types of research approaches that can advance both scientific knowledge and development impact. By placing socio-economic aspects at the centre of action, it facilitates a more grounded approach to dryland management in which some degradation is acknowledged as inevitable. Application and testing of the principles on the body of work by the CRP-DS demonstrated that systems approaches are providing new insights into complex dryland problems brought about by multiple drivers, better accounting for (contextual)

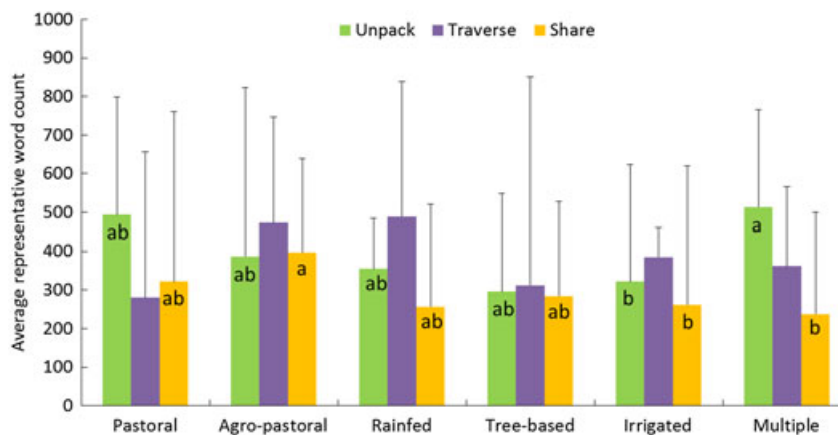


Figure 3. Representative word counts across different agricultural systems per principle. Bars indicate standard deviation. Different letters indicate statistically significant differences in word counts at 95% confidence level. [Colour figure can be viewed at wileyonlinelibrary.com]

complexity and uncertainty and delivering options through which the risks can be anticipated, assessed and managed (Öborn *et al.*, 2017). Taking a systems approach creates a more complete and realistic picture in which solutions can be situated. It allows researchers to better match supply (the research) with demand and impact (sustainable dryland development). It also permits the context and needs of target beneficiaries – the dryland poor – to be addressed in direct relation to the available options. This supports work that developed in parallel to the original DDP (Ostrom, 2009; Ostrom & Cox, 2010; Ostrom & Basurto, 2011) outside of the dryland systems context, which moves beyond the identification of particular solutions as panaceas and better appreciates complexity.

Underpinning each integrative principle is a focus on farming systems and livelihood portfolios, supported by inter- and trans-disciplinary approaches. This reinforces a global trend which has seen increased donor and science funding that is targeting the world's 'grand challenges' (Ledford, 2015; Van Noorden, 2015), and which recognizes that many urgent problems are driven by the interaction of multiple factors and require equally cross-cutting solutions. The CGIAR Research Programme on Dryland Systems research has contributed significantly towards the development of new, integrated methodologies for systems research, building from the disciplinary diversity within the CGIAR system. Nevertheless, consideration of trade-offs among multiple options was negatively correlated with inter- and trans-disciplinarity. This suggests research into trade-offs is as yet (too) narrowly framed in the literature and requires new combinations of disciplinary expertise and knowledge. This finding is particularly noteworthy given growing interest in 'nexus' approaches and the quest for solutions that encompass water-energy-food security linkages (Ringler *et al.*, 2013). It is also relevant for the SDGs which require careful and strategic implementation across all 17 goals and 169 targets. Future research that widens analysis of trade-offs based on the principles in the new DDP could facilitate SDG achievement.

Several papers in our sample applied *Unpack*, with words associated with characteristics under that principle appearing 446 times – the highest frequency for any of the principles. *Unpack* can be mapped most easily onto the 2007 DDP (see Table I, principles 1–3) and fits neatly with the disciplinary expertise brought together within the CRP-DS (CGIAR, 2015). Research that *Unpacked* and *Traversed* interactions between value chains in a dryland context was generally less ubiquitous than that on dryland social-ecological systems and livelihoods in the wider literature too, suggesting this gap is not just related to our sample. Focus on interactions between networks of value chains is relatively new in dryland contexts and did not feature in the 2007 DDP (Reynolds *et al.*, 2007). This implies that dryland researchers need to learn from experiences in other systems (cf. Stringer *et al.*, 2008), where networked value chain analyses are more fully developed, particularly if private sector value chain actors and investor perspectives are to be accommodated in dryland development interventions.

Traverse is largely supported by integrated modelling, participatory and learning approaches in the literature (e.g. Alkemade *et al.*, 2013; Alam *et al.*, 2015; Ladha *et al.*, 2016). These extend beyond single spatial scales and provide decision makers with information over multiple time frames, aiding development planning (Stringer *et al.*, 2014). They can also capture the multiple mobilities in drylands as people's livelihoods shift according to their asset base and the dynamic biophysical context (Okpara *et al.*, 2016b). Integrated modelling approaches further appeal to multiple sectors and operationalize nexus approaches (Mulligan *et al.*, 2016). However, capturing multiple knowledges across sectors and scales (including both slow and fast variables) requires research *in* development and approaches informed by the social sciences which we consider under *Share*. This expertise is not unique to the dryland context, whereas the specific nature of dryland biophysical processes results in greater dryland specialism amongst biophysical and environmental scientists. This demonstrates the need to encourage social scientists with relevant skills and approaches under *Traverse* and *Share* principles to adapt their approaches for application in the drylands, where the problem context is specific, but for which existing solutions can be usefully adapted and tested. It also highlights a need for partnerships that engage dryland and non-dryland researchers in order to target those methodological areas where competences are currently lacking amongst dryland researchers (cf. Pinske & Kolk, 2012; Akhtar-Schuster *et al.*, 2016).

Research under *Share* featured least strongly in the papers analysed, with few papers applying this principle in irrigated, rainfed and 'multiple' systems but slightly more within agro-pastoral systems. Higher *Share* scores in African sub-regions illustrate a strong participatory research tradition in Africa. In both West and East Africa, there is a long history of participatory research approaches that can facilitate *Sharing* (Hall, 2005), despite perceptions of high resource investments required to utilize participatory approaches.

Research *in* development that *Unpacks* interactions and *Traverses* scales, sectors and stakeholders supports *Sharing* via upscaling, out-scaling and impact (Righi *et al.*, 2011). It can also help to avoid interventions that focus on narrowly defined technologies that are assumed to be more widely applicable and successful, but which are not tested in specific dryland social-ecological contexts (Coe *et al.*, 2014). In contrast to Reynolds *et al.*'s (2007) focus on experiential learning from monitoring, research *in* development approaches focus on social learning processes that change understanding through peer-to-peer interactions. New ideas and practices then become situated beyond individuals or groups, at the scale of social units or society (Pahl-Wostl, 2009; Reed *et al.*, 2010; UNDP, 2010). Research comprehensively encompassing the characteristics across the three integrative principles fits a research *in* development model more closely than it does a research *for* development model. With donors now starting to recognize the need to emphasize a strong understanding of context (CGIAR, 2015), the

new DDP's integrative principles can be used to assess projects for funding suitability. They can also inform dryland scientists in their research design and approaches, and evaluators in assessing development impact.

Findings from our application of the three integrative principles raise important questions about the content of scientific papers and whether impacts are necessarily and reasonably captured and reported as an inherent part of research. Consequently, *Share* may be under-represented in our sample relative to *Unpack* and *Traverse*. Our sample focused on English language publications, with different regions in the sample also publishing in other languages. Language barriers could inhibit *Sharing* and *Traversing*, making impact harder to capture. That inclusion and empowerment of disadvantaged groups were not correlated to any other characteristic could either point to a lack of attention to differential impacts and how disadvantaged groups are affected, or discussion of scientific and impact-related project findings commonly being separate. The relatively short duration of the CRP-DS means that impacts such as empowerment may yet emerge, despite evidence of some engagement in co-productive approaches and empowering research processes. This further suggests that careful consideration is needed during programme evaluation regarding the indicators used to measure impact. Typically within the CGIAR system, monitoring and evaluation of science and development research use indicators that represent end points (CGIAR, 2015), whereas indicators that allow assessment of a process of *Sharing* and empowerment would be more suitable under a research *in* development model.

CONCLUSION

This paper has empirically derived eight characteristics, distilled into three integrative principles to transform dryland science and development, extending and advancing the DDP to make it actionable and relevant in the current global dryland context. While the new DDP has been applied in dryland systems, it can be further tested and refined for other agri-food systems. Empirical analysis has demonstrated the importance of the characteristics and integrative principles that underpin the new DDP and which frame a future research agenda.

- *Unpacking* relationships and interactions in dryland systems and livelihood portfolios can help to identify opportunities and risks for socio-technical innovation and investment to adapt to multiple interacting drivers of change at different spatial and temporal scales.
- *Traversing* scales and sectors can improve co-creation, availability of and access to options, shaped and owned by land users and other value chain actors. This enables a more contextual, people-centred focus in assessing risks, trade-offs and vulnerabilities, supporting sustainable, resilient and efficient pro-poor value chains. A networked approach to value chains can enable context-specific analysis and facilitate more inclusive, participatory governance reform.

- *Sharing* knowledge, learning and experience to empower dryland communities, researchers, policymakers and other stakeholders is important to reduce trade-offs and externalities, leverage no-regrets options and avoid unintended consequences. This is especially important in drylands where feedbacks, uncertainties and non-linearities characterize the system. Current knowledge is weakest in terms of understanding social processes such as social learning, decision-making behaviour and power balances within coupled social-ecological systems.

Enacting the three integrative principles together, the new DDP calls for the operationalization of research *in* development processes, and a shift away from research *for* development. This catalyses solutions that move beyond integrating local and traditional knowledge with science (cf. Reynolds *et al.*, 2007) towards partnerships and co-production that meaningfully engage stakeholders from relevant sectors and scales. As the first paper grounded in robust empirical analysis of cutting edge dryland science and development, the new DDP can be used to advance sustainable dryland agricultural livelihoods in the context of the 2030 Sustainable Development Goals.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Table S1. Keywords and word combinations and weights attached for representativeness to each characteristic.

Table S2. Regional representative word counts per principle and characteristic.

Table S3. Representative word counts across different agricultural systems per principle and characteristic.

Table S4. Correlations between representative word counts per characteristic across the total sample of papers considered.

Table S5. Correlations between representative word counts per principle across the total sample and regional sets of papers considered.

Table S6. Case studies from the CRP-DS that illustrate each of the three integrative principles from the new DDP.

Appendix S1. Literature review.

Appendix S2. Qualitative analysis.