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Review

Systems approaches to innovation in crop protection. A systematic literature review

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ABSTRACT

The objective of this paper is to explore the extent to which systems approaches to innovation are reflected in the crop protection literature and how such approaches are used. A systematic literature review is conducted to study the relation between crop protection and systems approaches to innovation in 107 publications. The analysis of the crop protection literature demonstrates that only a small fraction is systems-oriented as compared to the bulk of publications with a technology-oriented approach. The analysis of agricultural innovations systems literature shows that, although crop protection is addressed, the potential of this systems approach remains largely unexplored for crop protection innovation. A large share of the publications included in this review focus on cropping or farming 'systems' while 'innovation' often equals the development, transfer, adoption and diffusion of crop protection technologies at farm level. There is relatively little attention for the institutional and political dimensions of crop protection and the interactions between farm, regional and national levels in crop protection systems. The traditional division of roles and responsibilities of researchers as innovators, extension personnel as disseminators, and farmers as end-users, is challenged only to a limited extent. The majority of publications discusses ways to optimise existing features of crop protection systems, without exploring more structural transformations that may be required to enhance the resilience of crop protection systems.

1. Introduction

For a long time, crop protection research mainly focussed on the curative control of pests, diseases and weeds. Research was primarily mono-disciplinary and cause-effect oriented, and innovation often equalled the development, transfer and adoption of single-component technologies such as new crop varieties or agrochemicals (Kropff et al., 2001). Although such research has significantly contributed to increased agricultural production, the extensive use of agrochemicals in particular created new problems. Examples are negative effects on food-safety, public health and the environment (e.g. Richards et al., 1987; Ying and Williams, 1999), and the development of herbicide resistant weed populations in crop production systems (e.g. Moss, 2003). This resulted in a growing awareness that more comprehensive changes in crop production systems are needed to achieve sustainable crop protection innovations (Lewis et al., 1997). Consequently, this led to suggestions for a shift from technology-oriented approaches to more systems-oriented approaches – that consider innovation as a combination of technological and non-technological (e.g. social, institutional) advances across different levels (e.g. plot, farm, region) (Leeuwis, 2004) – to support integrated and holistic analyses of crop protection systems (e.g. Birch et al., 2011; Savary et al., 2012).

In the broader agricultural innovation literature, such a shift from technology-oriented approaches to systems-oriented approaches to innovation has indeed taken place. Based on a meta-review by Klerkx et al. (2012c), four evolving approaches to agricultural innovation have been identified (Table 1). The Transfer of Technology (TT) approach reflects the idea that researchers develop knowledge and technologies, which are then transferred 'top-down' by extension services to farmers or other end-users (Rogers, 1962). Awareness of the weaknesses of technology-oriented approaches initiated thinking about more systems-oriented approaches to innovation (Chambers and Jiggins, 1987; Giller et al., 2008). The Farming Systems (FS) approach is a response to the lack of attention for the context-specific social–cultural, economic and agro-ecological drivers that influence the performance of

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Table 1
Overview of the four approaches to agricultural innovation (based on: Klerkx et al., 2012c; World Bank, 2006).

Approach	Technology-oriented approach	Systems-oriented approaches		
	Transfer of technology (TT)	Farming systems (FS)	Agricultural knowledge and information systems (AKIS)	Agricultural innovation systems (AIS)
Era	1950s–1980s	1980s–1990s	1990s–2000s	2000s–onwards
Key-objectives	Transfer, diffusion and adoption of technology	Contextualise agricultural research and technology	Build local capacities, empower farmers	Enhance systems capacity to generate and respond to change
Scope	Increase global agricultural productivity	Identify and alleviate livelihood constraints	Collaborate, integrate different types of knowledge for sustainable development	Generate institutional change
Core elements	- Technology packages - Enhance efficiency of research transfer	- Locally adapted knowledge and technology	- Joint knowledge production and learning - Value chain approach	- Institutional analysis - Stakeholder analysis
Flow of innovation	Top-down	Top-down	Bottom-up	Multi-directional
Key intervention approach	- Technology dissemination through extension - Use mass media to facilitate adoption	- Farmer consultation to inform research - Surveys to develop farm typologies, modelling of innovation impact	- Conduct participatory research - Implement joint learning activities	- Establish and implement multi-actor innovation platforms
Role of farmers	- Adopters of technologies	- Adopters of knowledge and technologies - Source of information	- Experimenters - Experts	- Partners - Entrepreneurs - Part of innovation network
Role of research and researchers	- Developers of knowledge and technologies	- Experts	- Capacity builders - Facilitators of learning	- Actors to enhance innovation capacity in the system - Members innovation network
Strengths	- Enables rapid technological progress - Enhances agricultural productivity	- Technologies are developed in the specific context at farm level	- Integrates different types of knowledge (scientific, expert and farmer), skills and experiences - Contextualises the approach and considers value chain dynamics	- Multi-level focus - Considers institutional and political dimensions of change - Enhances resilience of the agricultural system
Weaknesses	- Disregards farmers in technology development - Disregards adoption context	- Focuses on farm and field level only with limited attention for multi-level interactions	- Applies a local focus with limited attention for multi-level interactions - Ignores structural power inequalities between actors - Entails high costs - Encounters challenges in scaling up and scaling out	- Complicates delineation of system - Lacks empirical evidence of practical impact and value

Note: The approaches are not mutually exclusive. Elements of, for example, the technology-oriented approach can form part of the different systems-oriented approaches.

agricultural innovations at the level of the individual field, the farm, or a collection of farms (e.g. Altieri, 1984; Biggs, 1995; Giller, 2013). A gradual shift from top-down to bottom-up approaches to agricultural innovation is reflected in the Agricultural Knowledge and Information Systems (AKIS) approach (e.g. Engel, 1995). This shift materialised in participatory research that seeks to foster joint learning between researchers, extension personnel, farmers and other value chain actors as a basis for sustainable agricultural development (Leeuwis and Pyburn, 2002; Pretty, 1995; Röling, 1990, 1992). Compared to the other systems-oriented approaches, the agricultural innovations systems (AIS) approach has more attention for the institutional and political dimensions of change processes (Hounkonnou et al., 2012; Leeuwis, 2000). Innovation is considered as a process that is shaped by interactions between actors and institutions inside and outside the agricultural sector (Hall et al., 2003; Klerkx et al., 2010; Schut et al., 2013). The focus of such processes can be 'optimisation-oriented' – i.e. to optimise existing features of the system such as exchange of knowledge – or be more 'transformation-oriented' – i.e. to question how knowledge is produced in the first place (cf. Kilelu et al., 2013; Weber and Rohracher, 2012).

Although a shift from technology-oriented to systems-oriented approaches to crop protection innovation has been advocated (e.g. Lewis et al., 1997), there is limited understanding of the extent to which such an evolution has actually taken place. The objective of this systematic review is to explore how systems approaches to innovation are reflected and used in the crop protection literature.

2. Systematic review methodology

To study the evolution of systems approaches to innovation in the crop protection literature, a two-step systematic literature review was conducted. First, we limited our search to crop protection literature[1] using the web-based search engine ISI Web of

[1] TS=((((((nematode* AND crop) OR (nematode* AND plant)) OR ((disease* AND crop) OR (disease* AND plant)) OR ((bacteria* AND crop) OR (bacteria* AND plant)) OR ((virus* AND crop) OR (virus* AND plant)) OR ((insect* AND crop) OR (insect* AND plant)) OR ((pest* AND crop) OR (pest* AND plant)) OR ((termite* AND crop) OR (termite* AND plant)) OR ((rodent* AND crop) OR (rodent* AND plant)) OR ((fung* AND crop) OR (fung* AND plant)) OR ((mite* AND crop) OR (mite* AND plant)) OR ((bird* AND crop) OR (bird* AND plant)) OR ((aphid* AND crop) OR (aphid* AND plant)) OR (weed*)) AND (management OR protect* OR prevent* OR control or eradicat*)) OR ("crop protection" OR "plant protection") OR (("chemical control" AND crop) OR ("chemical control" AND plant) OR ("biological control" AND crop) OR ("biological control" AND plant) OR ("mechani* control" AND crop) OR ("mechani* control" AND plant))).

Knowledge(SM). Topic Search (TS) was used to identify publications that refer to crop protection in title, abstract, author keywords and keywords plus®. The search was further narrowed down to English language 'articles' and 'reviews' that were published between 1 January 1945 and 31 December 2012 and indexed in the Science Citation Index or the Social Science Citation Index. The search was performed in October 2013 and resulted in 82,425 publications, including peer-reviewed research papers, review papers, proceedings papers and book chapters. Next, Topic Search was used to search the selection for technology-oriented[2] publications and systems-oriented[3] publications.

The systems-oriented publications were studied in more detail. Abstracts were read and publications with limited relevance to crop protection or agriculture in general were excluded from the search. The remaining publications were systematically analysed. The abstract, introduction and conclusion of each of the publications were read and an inventory of the publications' geographical focus, author affiliation, level of analysis, year of publication, source title and attention for specific crops or crop protection areas (e.g. pests, diseases, weeds, etc.) was made. Next, the publications were electronically analysed in Adobe Acrobat™ using 61 keywords (Table 2). For each keyword, the number of appearances in the title, abstract, keywords and main body of the text (excluding figures, tables, captions, acknowledgement and references) was quantified. Non-electronic publications were analysed manually. Appearance of keywords was analysed, but the number of keyword hits were not quantified. Keywords 1–11 were used to quantify the number of appearances of 'system' and 'innovation', and to examine to what type of 'system' the publication referred to. Keywords 12–46 were purposefully and progressively formulated so as to reflect the main themes and features of the four approaches to innovation. Additionally, keywords 47–61 were formulated to explore the publications' specific attention for different segments of value chains. Keywords are not mutually exclusive; i.e. a specific keyword (e.g. production or yield) can have different meaning depending on the context in which it is being used. Consequently, during the analysis of the publications, the meaning and use of the keywords were verified, enabling us to categorise the publications (Section 3).

Second, the attention for crop protection in AIS literature was analysed because the first search, limited to crop protection literature, may have overlooked the more holistic publications in which crop protection is addressed, but not explicitly mentioned in the title, abstract or keywords. AIS was chosen as it represents the most comprehensive systems approach to innovation to date (cf. Klerkx et al., 2012c; World Bank, 2006). The same time period, search engines and databases were used as for the previous search to conduct a Topic Search for English language articles and reviews that refer to AIS.[4] The 23 publications that resulted from the search were fully read and analysed for their interpretation of the AIS approach and their specific reference to crop protection (Section 4).

Table 2
Keywords that were used to analyse the systems-oriented crop protection publications in Adobe Acrobat™.

General keywords	1. Innovation
	2. System
	3. Production system
	4. Cropping system
	5. Ecosystem
	6. Agro ecosystem
	7. Innovation System
	8. RIS (Regional Innovation System)
	9. NIS (National Innovation System)
	10. SIS (Sectoral Innovation System)
	11. TIS (Technical Innovation System)
TT keywords	12. Techn*
	13. Transfer (related to technology)
	14. Adopt* (related to technology)
	15. Diffusion (related to technology)
	16. Mass-media
	17. National Agricultural Research System/NARS
	18. Agricultural Research (System)
	19. Yield
	20. Extension
	21. Education
FS keywords	22. Farming system
	23. Locally adapted
AKIS keywords	24. AKIS
	25. Knowledge
	26. Knowledge management
	27. Knowledge system
	28. ICT
	29. Information (techn*)
	30. Participant*
	31. Participatory research
	32. Communication
	33. Learning
	34. Social learning
AIS keywords	35. Institution*
	36. Policy
	37. Regulation
	38. Politic*
	39. Subsidi*
	40. Network
	41. Platform
	42. Multi-stakeholder
	43. Multi-level
	44. Interdisci*
	45. Multi-disciplina*/multidiscipline*
	46. Negotiation
Value chain keywords	47. Value chain
	48. Supply chain
	49. Seed
	50. Breeding
	51. Production
	52. Fertilizer
	53. Herbicide
	54. Insecticide
	55. Pesticide
	56. Processing
	57. Trade
	58. Market(ing)
	59. Retail
	60. Consum*
	61. Property rights/patents

Note: The asterisk (*) that is used in some of the keywords (e.g. keyword 12, Techn*) resembles a wildcard character. The asterisk can be substituted by any other subset of characters (e.g. Techn-ology, - ique, -ological).

3. Systems approaches and innovation in crop protection literature

Of the 82,425 crop protection publications, 7558 (9.2%) make specific reference to the development, transfer, adoption, dissemination or diffusion of technologies. Only 104 publications (0.1%) address systems in relation to innovation. A more or less parallel linear increase of technology-oriented publications (7.6% per year) compared to the larger body of crop protection literature (8.4% per year) can be observed during the period under review. The linear increase of systems-oriented publications over the same period of time is slightly steeper (10.8% per year) (Table 3, Fig. 1).

After screening the abstracts of the 104 systems-oriented publications, 20 non-crop related publications (e.g. on human or animal health) as well as publications with limited relevance (e.g. microbiology, insect–plant interactions) were excluded from the

[2] TS = (techn*) AND TS = (develop*) OR TS = (transfer) OR TS = (adopt*) OR TS = (disseminat*) OR TS = (diffus*).
[3] TS = (system*) AND (innovation*).
[4] TS=("agricultur* innovation system*").

Table 3
Crop protection publications and the relative share of technology-oriented and systems-oriented crop protection publications.

	All crop protection publications	Development, transfer, dissemination, diffusion and adoption of technology	Systems approaches to innovation
Number of publications (% of total)	82,425 (100.0%)	7558 (9.2%)	104 (0.1%)
Range of publication years	1945–2012	1986–2012	1991–2012
Average publications per year (1991–2013)	3640.7	342.7	4.7
Average linear increase of publications per year (1991–2013)	7.6%	8.4%	10.8%
Top-3 source titles (% of total)	1. Weed technology (2.3%) 2. Crop protection (2.0%) 3. Weed science (1.8%)	1. Crop protection (1.9%) 2. Pest management science (1.3%) 3. Weed technology (1.3%)	1. Agricultural systems (5.8%) 2. Experimental agriculture (4.8%) 3. Field crops research (3.8%)
Top-3 web of science categories (% of total)	1. Plant sciences (25.4%) 2. Agronomy (18.1%) 3. Entomology (13.4%)	1. Plant sciences (23.2%) 2. Agronomy (18.6%) 3. Entomology (10.9%)	1. Agronomy (34.6%) 2. Agriculture multidisciplinary (21.2%) 3. Environmental sciences (15.4%)

review. Of the remaining 84 publications, 74 were available and analysed electronically and 10 were analysed manually. Of the publications, 73% were published between 2007 and 2013.Thirteen publications were reviews. The top-3 journals in which 18% of the 84 systems-oriented publications were published have a broader focus on agriculture and crop research as compared to the general body of crop protection literature and the technology-oriented publications (Table 3).

Of the 84 publications, 81% discuss multiple crop protection issues (e.g. bacteria, virus, fungi). The combination ‘disease’, ‘pest’ and ‘weed’ was most popular as it appeared in 49% of the publications. Crop protection is mainly addressed in relation to multiple crops or mixed cropping systems. Cropping systems involving rice (15%) were most frequently represented. Regarding the geographical orientation, the share of publications focussing on agriculture in developed, industrial countries (mainly North America, Europe and Australia: $n = 30$, 36%) is fairly similar to the share of publications focussing on agriculture in developing countries (Asia, Africa and Mid/Latin America, or developing countries in general: $n = 34$, 40%). The remaining publications ($n = 20$, 24%) have a more global orientation.

The analysis of the 84 publications was twofold. First, the publications were analysed for their reference to elements of the four approaches to innovation presented in Table 1. Elements of TT ($n = 44$, 55%) and FS ($n = 43$, 54%) dominated the publications, followed by elements of AKIS ($n = 37$, 46%) and AIS ($n = 36$, 45%). Secondly, the publications were categorised according to the most predominant approach to innovation reflected in the publication. During this step a publication would be categorised as either TT or FS or AKIS or AIS. Eventually, 80 of the 84 publications were

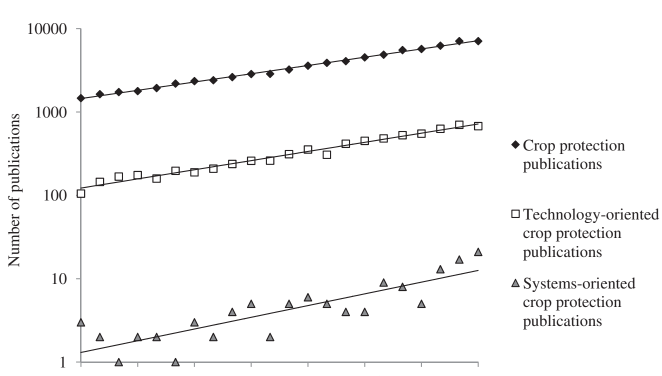

Fig. 1. Exponential increase of crop protection publications and the relative share of technology-oriented and systems-oriented crop protection publications between 1991 and 2013 expressed on a logarithmic scale.

categorised under any of the four approaches (Table 4). Of the four publications that were not categorised, three were crop protection reviews without a single predominant approach to innovation. The remaining 10 crop protection review papers found among the 84 publications were categorised quite equally under the different approaches to innovation (TT = 2, FS = 3, AKIS = 3 and AIS = 2).

For each of the categories, a gradual increase of publications per year can be observed (Fig. 2). The analysis of the geographic orientations demonstrates that AKIS publications focus less on developed countries (22%) than on developing countries (44%), and that AIS publications generally had a less global orientation (6%) compared to the publications reflecting the TT, FS and AKIS approaches (23%, 17% and 33%, respectively). The first authors of the publications were mainly researchers based at universities ($n = 44$, 52%) or international agricultural research institutes ($n = 27$, 32%), followed by researchers based at national agricultural research institutes ($n = 6$, 7%), agrochemical industry ($n = 2$, 2%), governments ($n = 2$, 2%), consultancy companies ($n = 2$, 2%) and farmer representative bodies ($n = 1$, 1%). The keyword analysis showed that the average number of keywords appearing in the 80 publications gradually increased, when moving from the TT approach towards the AIS approach (TT = 25%, FS = 29%, AKIS = 34% and AIS = 37%).

3.1. Transfer of technology approach

In the crop protection publications categorised under the TT approach ($n = 26$, 33%), the development, transfer and adoption of crop protection technologies (including technologies, techniques or practices) are central. In these publications ‘systems’, for instance, referred to cropping systems (e.g. de Barros et al., 2009; Pelzer et al., 2012; Tixier et al., 2008) or to agricultural research systems (e.g. Chandranna et al., 2009; D’Emden et al., 2006; Huttner et al., 1995; Lalitha, 2004). ‘Innovation’ often equalled technology (e.g. Green, 2007), and keyword count shows that the adoption of technology is an important topic in 65% of the TT publications. In 42% of the TT publications, technology adoption is studied at the farm level. In several other publications, national level agricultural research systems (NARS) are considered and how the existence and quality of its physical infrastructure (e.g. research and development facilities and access to inputs) and knowledge infrastructure (e.g. ICT and mass media) influence the efficient, timely and fair transfer, adoption and diffusion of crop protection innovations (e.g. Chandranna et al., 2009; D’Emden et al., 2006; Huttner et al., 1995; Lalitha, 2004; Ozcatalbas and Brumfield, 2010). In these publications, the role of governmental agricultural extension services in crop protection innovation is central.

Different groups of TT publications can be identified. First, there are publications in which innovation equals successful linear

Table 4
Crop protection publications categorised according to the predominant approach to innovation reflected in the publication.

Approach (#)	Publications
TT (*n* = 26, 33%)	Affholder et al., 2010; Boizard et al., 2012; Chandranna et al., 2009; D'Emden et al., 2006; de Barros et al., 2009; Gibson et al., 2008; Granatstein and Mullinix, 2008; Green, 2007; Hedin et al., 1994; Hofs et al., 2006; Huttner et al., 1995; Kempenaar and Lotz, 2004; Khumairoh et al., 2012; Lalitha, 2004; Loyce et al., 2012; Mader and Berner, 2012; Ozcatalbas and Brumfield, 2010; Pandey et al., 2010; Popp, 2011; Thorsness et al., 2007; Tixier et al., 2008; Udensi et al., 2012; van der Weide et al., 2008; van Noordwijk, 1999; Vanloqueren and Baret, 2008; Waller et al., 1998; Zheng et al., 2010
FS (*n* = 18, 23%)	Blazy et al., 2009a, 2009b, 2010; Bohringer, 1991; Chauhan et al., 2012; Delmotte et al., 2011; Dixit et al., 2011; Entz et al., 2002; Franke et al., 2003; Germer et al., 2011; Glancey et al., 2005; Kennedy and Storer, 2000; Lestrelin et al., 2012; Li et al., 2011; Llewellyn et al., 2012; Sheppard et al., 2011; Siddique et al., 2012; Vogl and Vogl-Lukasser, 2003
AKIS (*n* = 18, 23%)	Chauhan et al., 2012; De Wolf and Isard, 2007; Doohan et al., 2010; Erenstein and Laxmi, 2008; Jordan et al., 2002; Juroszek and von Tiedemann, 2011; Krupnik et al., 2012; Kurstjens, 2007; Le Bellec et al., 2012; Llewellyn, 2007; Llewellyn et al., 2005; Muhr et al., 2001; Pelzer et al., 2012; Prudent et al., 2007; Saidou et al., 2004; Salinger et al., 2005; Styger et al., 2011b; Veisi, 2012
AIS (*n* = 18, 23%)	Chandler et al., 2008, 2011; den Hond et al., 1999; Erenstein et al., 2012; Ferdinands et al., 2011; Gerowitt et al., 2003; Giller et al., 2011; Lahmar, 2010; Lanteri and Quagliotti, 1997; Lenne et al., 2007; Milford, 2003; Nicholas and Durham, 2012; Probst et al., 2012; Rola et al., 2010; Selvaraju et al., 2011; Sims et al., 2012; Styger et al., 2011a

Note: Four publications were not categorised: Deliopoulos et al., 2010; Nesme et al., 2010; Rubiales and Fernandez-Aparicio, 2012; Stern and Cooper, 2011.

development, transfer and/or adoption of a crop protection technology that can be mechanical, chemical, biological, or a combination of these (e.g. Ozcatalbas and Brumfield, 2010). This group of publications includes two publications on crop protection technology development by the agrochemical industry (Green, 2007; Thorsness et al., 2007). Second, there is a group of publications in which the performance and impact of crop protection technologies are assessed on the basis of the three classic pillars of sustainability (cf. Hansmann et al., 2012; Van Cauwenbergh et al., 2007): their socio-cultural acceptability, economic viability and environmental impact (e.g. Boizard et al., 2012; Chauhan et al., 2012; Selvaraju et al., 2011). Although the importance of – for example – farmer training, farmer collaboration or access to credit is mentioned (e.g.

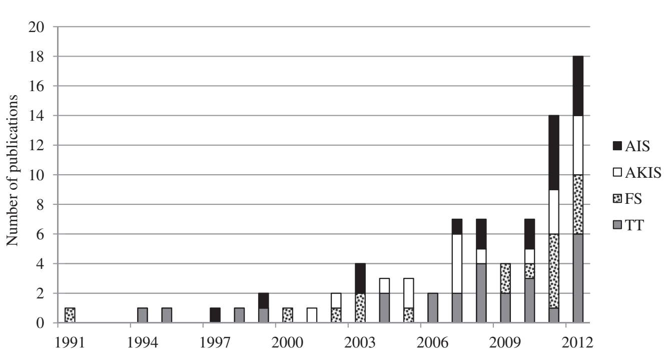

Fig. 2. Number of publications per approach between 1991 and 2013 (TT = Transfer of Technology, FS = Farming Systems, AKIS = Agricultural Knowledge and Information Systems, and AIS = Agricultural Innovation Systems).

Khumairoh et al., 2012), the key focus of these publications is on the development, transfer or adoption of technologies (e.g. Hedin et al., 1994; Pandey et al., 2010; Waller et al., 1998). A third group of publications go beyond the classic pillars of sustainability. These publications focus on institutional and political factors influencing adoption of crop protection technologies by farmers, such as land tenure (Udensi et al., 2012), policy changes (Affholder et al., 2010), agricultural regulations and subsidies (de Barros et al., 2009) and market and consumer demands(Granatstein and Mullinix, 2008). In particular the biotechnology publications pay attention to the regulatory and legal dimensions of technologies, such as intellectual and property rights (e.g. Huttner et al., 1995). Despite the attention for the non-technological dimensions of innovation, the transfer of technology from researchers to farmers is still the dominant approach followed in these publications.

3.2. Farming systems approach

The FS publications (*n* = 18, 23%) focus specifically on the heterogeneity of farming and crop production systems, the context in which farming takes place and the need to adapt and contextualise crop protection technologies and management strategies (e.g. Blazy et al., 2009a, 2010; Chauhan et al., 2012; Franke et al., 2003; Li et al., 2011; Llewellyn et al., 2012). Of the FS publications, 61% focus mainly on farm level analysis, and often farm typologies are used to describe and analyse farm heterogeneity (e.g. Blazy et al., 2009b; Li et al., 2011).

Generally, FS publications analyse the impact of different crop protection technologies on crop productivity (Blazy et al., 2009a; Dixit et al., 2011; Entz et al., 2002; Siddique et al., 2012). Understanding different types of land, water and labour constraints in relation to the adoption and diffusion of crop protection technologies is another important topic in FS publications (Bohringer, 1991; Chauhan et al., 2012; Lestrelin et al., 2012). A number of publications link the performance and impact of crop protection technologies to economic viability (e.g. access to credit, labour costs or savings) and agro-environmental variation (e.g. soils or, rainfall) (e.g. Blazy et al., 2009b; Llewellyn et al., 2012). Such factors are used to predict the receptiveness of farmers to technical innovations (e.g. Franke et al., 2003). The majority of the FS publications also focusses on value chain segments other than 'crop production', particularly marketing (Blazy et al., 2010; Entz et al., 2002; Lestrelin et al., 2012; Sheppard et al., 2011), but also issues related to breeding (Siddique et al., 2012), food processing (Glancey et al., 2005), food consumption (Entz et al., 2002; Germer et al., 2011) and agricultural subsidies (Blazy et al., 2010; Sheppard et al., 2011) are discussed.

Although some publications mention institutional (e.g. policies and subsidies) and political dimensions (e.g. pressure groups, controversies regarding Genetically Modified Organisms (GMO) and pesticide politics) related to technological innovations (e.g. Germer et al., 2011; Kennedy and Storer, 2000), there is little structural analysis of these dimensions within the FS publications. Lastly, in several publications farmer participation in research is advocated or discussed but not implemented (e.g. Blazy et al., 2010; Siddique et al., 2012).

3.3. Agricultural knowledge and information systems approach

The AKIS publications (*n* = 18, 23%) were published from 2001 onwards. AKIS publications primarily present farmer participatory research as a means to foster two-way communication between farmers and researchers. According to Doohan et al. (2010) and Styger et al. (2011a), participatory research provides a better understanding of farmer perceptions on crop protection and it enables the inclusion of farmers' expertise in developing and locally adapting technologies. Furthermore, it can enhance farmer responsibility and ownership over technology development and, more generally, over change processes (Le Bellec et al., 2012). Salinger et al. (2005), for instance, describe the participation of farming communities in pilot projects on agro-meteorological modelling to forecast the development of weeds, insect pest and diseases problems. Farmer-managed, research-supported on-farm experiments, field days and farmer field schools are mentioned as popular participatory research methods to jointly design, develop and adapt technologies (Krupnik et al., 2012; Le Bellec et al., 2012; Muhr et al., 2001; Prudent et al., 2007).

Learning-based approaches form an important element in the AKIS publications. Three types of joint (or social) learning are distinguished; farmer-centred learning (e.g. Styger et al., 2011a), farmer-research learning (e.g. Krupnik et al., 2012), and multi-actor learning (e.g. Jordan et al., 2002). Learning is framed as bringing together different types of knowledge, for example that of farmers, researchers and policymakers (Doohan et al., 2010; Salinger et al., 2005), or different scientific disciplines through interdisciplinary learning (Kurstjens, 2007). A combination of both is referred to as cross- or multi-disciplinary learning, for example when farmers, scientists from different disciplines and information technology specialists collaborate to predict pest or disease outbreaks (De Wolf and Isard, 2007; Jordan et al., 2002; Salinger et al., 2005). Compared to the FS approach, there is increasing attention for multi-actor collaboration and negotiation in platforms and networks (Le Bellec et al., 2012; Pelzer et al., 2012; Saidou et al., 2004).

Within the AKIS category, there is a wide variety of scopes. The majority of publications discusses market(ing), institutional dynamics and agricultural policies as part of a broader and more integrated perspective on crop protection (e.g. Pelzer et al., 2012; Prudent et al., 2007; Saidou et al., 2004). Publications by Ervin et al. (2011) and Salinger et al. (2005) stand out in terms of their holistic approach, i.e. discussing a broad range of biophysical, social–cultural, economic and institutional crop protection issues. Political issues still largely remain unexplored. In general, the added value of participatory, learning-based approaches is directly linked to better understanding of factors affecting the adoption of crop protection technologies (e.g. Ervin et al., 2011; Llewellyn, 2007; Llewellyn et al., 2005; Prudent et al., 2007; Veisi, 2012). Some authors stress that to enhance the contribution of research to developing sustainable crop protection solutions, structural changes in collaboration between actors in the agricultural sector, and innovative research approaches (e.g. action research) are required (e.g. Jordan et al., 2002; Krupnik et al., 2012).

3.4. Agricultural innovation systems approach

Of the publications (n = 18, 23%) with a prime focus on the AIS approach, 78% were published between 2007 and 2013. Keyword analysis demonstrates that the AIS publications are more holistic than publications in the other three categories, addressing a broad range of technology-oriented and systems-oriented topics (e.g. Erenstein et al., 2012; Lanteri and Quagliotti, 1997). Compared to the other approaches, the AIS publications in particular pay more attention to the institutional, policy and political dimensions of crop protection (Table 5).

Several authors describe and integrate the different agro-ecological, social–cultural, economic, institutional (including policy) and political dimensions of crop protection innovations (e.g. den Hond et al., 1999; Lalitha, 2004). Regarding the value chain segments, there is increased attention for trade, retail and consumption, whereas crop production and input supply (notably fertilizers and herbicides) take less central positions in the AIS publications as compared to publications in the other categories (Erenstein et al., 2012; Lenne et al., 2007; e.g. Milford, 2003).

Table 5
Keyword count demonstrating the appearance of keywords 'institution(s)(al)', 'policy' and 'politic(s)(al)' in crop protection publications categorised under the four different approaches to innovation.

Keyword	TT	FS	AKIS	AIS
Institution(s)(al)	19%	17%	39%	72%
Policy	35%	50%	56%	72%
Politic(s)(al)	15%	17%	6%	56%

AIS publications have a strong focus on analysing and understanding interactions between e.g. the supranational, national and local level (Gerowitt et al., 2003). For instance den Hond et al. (1999) explore the relations between the increasing globalisation and standardisation in the agro-chemical sector on the one hand, and the increasingly local, contextualised approaches to agriculture on the other hand. Additionally, authors refer to the impact of (policy) decisions taken at higher levels (e.g. at EU level) and how they can enable or constrain innovation at lower levels (e.g. at EU Member State level) (Selvaraju et al., 2011). Sims et al. (2012), for example, discuss how import taxes on steel, but not on imported agricultural machinery, can disadvantage local manufacturers in developing locally adapted agricultural equipment. The AIS approach is proposed to explore and better understand these multi-level interactions (e.g. Giller et al., 2011; Selvaraju et al., 2011).

In AIS publications on crop protection, there is more attention for multi-actor collaborations (including researchers, extension agents, equipment manufacturers, input suppliers, farmers, traders, and processors) as compared to publications dominated by the other approaches (e.g. Rola et al., 2010). Innovation networks or platforms are proposed to facilitate interaction and learning between actors (Chandler et al., 2008; Erenstein et al., 2012; Lahmar, 2010; Lenne et al., 2007; Sims et al., 2012).

A number of publications frame AIS as systems with clear boundaries, within which constraints that hamper the performance or impact of innovation can be measured and alleviated (e.g. Lanteri and Quagliotti, 1997; Vanloqueren and Baret, 2008). Some studies move away from innovations as technologies, techniques or practices, and describe innovations as inherently complex and unpredictable processes (e.g. Ferdinands et al., 2011; Lahmar, 2010; Probst et al., 2012; Styger et al., 2011a). This process-oriented focus broadens the discussions on what constitutes innovation in crop protection systems; from the development, transfer, adoption and adaptation of technologies, towards enhancing capacity in the crop protection system to generate and respond to change (e.g. Nicholas and Durham, 2012).

4. Crop protection in the agricultural innovation systems literature

The 23 publications that resulted from the search for AIS literature were all published between 1998 and 2013 (Table 6). Of these publications, 12 (52%) were published between 2010 and 2013. Nine publications were published in *Agricultural Systems*. There was no overlap between these 23 publications and the 104 publications that had resulted from the first search on systems approaches to innovation in crop protection literature.

The majority of publications acknowledge that agricultural innovation is embedded in complex interactions between social, cultural, biophysical, technological, economic, institutional and political dimensions which are rapidly changing and unpredictable (Brooks and Loevinsohn, 2011; Chave et al., 2012; Echeverria, 1998;

Table 6
Publications resulting from the search for Agricultural Innovation Systems (AIS) literature.

Approach (#)	Publications
AIS (23)	Agwu et al., 2008; Basu and Leeuwis, 2012; Brooks and Loevinsohn, 2011; Chave et al., 2012; Echeverria, 1998; Gijsbers and van Tulder, 2011; Horton and Mackay, 2003; Isaac, 2012; Kim et al., 2012; Klerkx et al., 2010, 2012a, 2012b; Leitgeb et al., 2011; Maat, 2007; Mapila et al., 2012; Morriss et al., 2006; Qaim, 2009; Raina, 2003a,b; Rivera and Sulaiman, 2009; Spielman et al., 2008; Temel et al., 2003; Tyagi, 2012

Horton and Mackay, 2003; Kim et al., 2012; Leitgeb et al., 2011; Tyagi, 2012). In descriptions of the AIS approach, authors mention the involvement of multiple actors and organisations representing local, national, regional and global levels in learning platforms and networks (Brooks and Loevinsohn, 2011; Gijsbers and van Tulder, 2011; Klerkx et al., 2010, 2012b; Leitgeb et al., 2011). In line with that, almost all AIS publications emphasize the need for improved coordination, collaboration and communication between actors in the agricultural system as a precondition for innovation (e.g. Tyagi, 2012). Although researchers, extension personnel, policymakers and farmers still fulfil central positions, there is increasing attention for the position of private sector representatives and consumers in the AIS publications (e.g. Chave et al., 2012; Gijsbers and van Tulder, 2011; Klerkx et al., 2010; Qaim, 2009; Spielman et al., 2008). Nevertheless, some authors conclude that the private sector (e.g. agribusiness, banks, traders, transporters and food processors and retailers) is generally weakly represented in multi-actor research and development processes (Agwu et al., 2008; Kim et al., 2012; Leitgeb et al., 2011). Klerkx et al. (2012a) and Temel et al. (2003) propose intermediary organizations to foster interactions between public and private actors in the agricultural system. Moreover, institutional dynamics related to trade, patents and property rights, taxes, agricultural subsidies, and biosafety and food safety standards are mentioned as factors affecting innovation in the agricultural sector (Gijsbers and van Tulder, 2011; Mapila et al., 2012; Qaim, 2009; Raina, 2003b). The majority of publications is optimisation-oriented, i.e. describing the need for optimising agricultural systems to enhance effective development and up-scaling of technological innovations (Isaac, 2012; Leitgeb et al., 2011; Morriss et al., 2006; Rivera and Sulaiman, 2009). Others, such as Klerkx et al. (2012a) argue that structural rethinking of technical, social and institutional configurations and actor roles is needed; representing a more transformation-oriented perspective on innovation.

Despite the relevance of these issues for crop protection, none of the publications analyses a complex crop protection problem using the AIS approach. Nevertheless, crop protection features in different ways. First, crop protection examples are used to illustrate the complex, multi-disciplinary and multi-level character of agricultural problems, for instance related to climate change. Leitgeb et al. (2011) use crop protection examples to underline that innovations are embedded in an institutional, socio-economic, biophysical and political context. Maat (2007) presents the bottlenecks for mechanised weed control in humid and sub-humid tropical zones. Both publications conclude that the suitability and performance of technologies should be assessed in the specific context in which farming takes place; one of the key features of the FS and the AIS approaches.

A second subset of publications presents crop protection examples to illustrate problems caused by unsustainable crop production practices, technology-oriented or top-down approaches to agricultural innovation (Gijsbers and van Tulder, 2011; Rivera and Sulaiman, 2009). Integrated approaches (e.g. Integrated Pest Management) or participatory research strategies (e.g. participatory plant breeding or farmer field schools) are presented as ways to develop more sustainable crop protection technologies (e.g. Brooks and Loevinsohn, 2011). Basu and Leeuwis (2012) discuss the system of rice intensification (SRI) in relation to weed and pest management and draw lessons from SRI's non-linear diffusion.

Thirdly, new technologies and approaches for crop protection are discussed. Two publications focus on the potential of biotechnology (including genetically modified, herbicide tolerant and insect resistant crops) as part of an AIS approach to control insect pests, diseases and viruses and to reduce labour-demands for weeding (Qaim, 2009; Raina, 2003b). Qaim (2009) concludes that: "Nonetheless, more research is needed to develop best practices for the transfer of technologies and know-how as well as the development and commercialization of GM crops"; a statement that better fits the TT approach. Besides biotechnology, biological pest control options are mentioned by Leitgeb et al. (2011) as part of an agricultural innovation policy.

The fourth way in which crop protection is used in AIS literature is by explicitly mentioning insects and diseases monitoring and control as key responsibilities of research and extension organisations in agricultural innovation systems (Gijsbers and van Tulder, 2011; Leitgeb et al., 2011). In these and several of the other publications, extension continues to be seen as an important "engine for innovation" (Rivera and Sulaiman, 2009). However, the conventional roles and mandates of extension personnel as facilitators of knowledge and technology transfer are challenged, and more attention for institutional innovations, such as the structural collaboration between public and private actors, is advocated (see also Agwu et al., 2008; Klerkx et al., 2012a; Raina, 2003a; Rivera and Sulaiman, 2009).

5. Analysis and discussion

Attention for systems-oriented approaches to innovation in the crop protection literature has increased rapidly over the past two decades. Since 1991, the average linear increase of systems-oriented publications has been higher than the technology-oriented publications. Despite this rapid growth, the relative share of publications with a technology-oriented approach still dominates the current crop protection literature. Based on our review, we conclude that 33% of the crop protection publications that emerged from our search for systems approaches to innovation were predominantly technology-oriented, and were – consequently – classified under the TT approach. It underlines the strength of our systematic review method, based on a critical analysis of systems approaches to innovation of crop protection literature, and a comparison with evolutions in thinking about systems approaches in the broader agricultural innovation literature. Our systematic review method also poses some challenges. In our categorisation of the publications, it is possible that we have miscategorised or overlooked holistic processes leading to publications reporting on technology development. Given the small amount of publications developed by agrochemical industry representatives (2%) and the predominant TT approach in these publications, further analysis of the use of systems approaches to innovation within the crop protection industry would be relevant. Although crop protection features in the 48% of the 23 AIS publications discussed in Section 4, the AIS approach as such has not been applied to study a complex crop protection problem, leaving its potential unexplored.

Based on this review, four cross-cutting themes related to systems approaches to crop protection innovation have been identified: (1) the different dimensions of crop protection, (2) the interactions between different levels, (3) the roles of and relations between different groups of actors, and (4) the perceptions on what comprises innovation in crop protection systems.

5.1. Multi-dimensional

Along with the evolution from technology-oriented to system-oriented approaches to innovation, there is increased attention for interactions between the biophysical, social–cultural, economic, institutional and political dimensions of innovation (e.g. Boizard et al., 2012). Many of the crop protection publications in this review use the classic sustainability pillars, in which crop protection innovations are discussed in relation to their social–cultural acceptability, economic viability and environmental impact. Notably, the biotechnology studies emphasise the institutional dimensions (regulatory frameworks and property rights) and political dimensions (consumer or political acceptance) of new crop protection technologies (e.g. Ervin et al., 2011; Rola et al., 2010). AIS publications use more holistic and integrated approaches to innovations in crop protection systems. A good example is the study by Nicholas and Durham (2012), who discuss pest and disease management in winegrowing within the broader framework of climate change, consumer preferences, policies and cultural barriers to change. However, despite the increased attention for interactions between the different dimensions of crop protection, comprehensive conceptual and analytical frameworks to guide multi-dimensional analysis are generally absent in the crop protection literature. Potential reasons for this are provided by Doohan et al. (2010) who claim that many researchers tend to (willingly or unwillingly) ignore dimensions that are beyond their discipline and field of expertise. Several other authors stress the need for inter- and multi-disciplinary research collaborations between crop protection researchers and other researchers as a prerequisite for robust multi-dimensional analysis of complex crop protection problems, or complex agricultural problems in general (e.g. De Wolf and Isard, 2007).

5.2. Multi-level

The review shows that the largest group of TT and FS crop protection publications focusses on farm level analysis. Within these studies, productivity increase at the farm level is usually the key indicator for successful innovation. For example studies by Affholder et al. (2010) and Blazy et al. (2010) analyse the relation between the adoption of innovative technologies (hybrid cultivars) and innovative management practices (improved fallow and intercropping) at farm level, and the overall farm performance (yield, labour efficiency and income). AKIS and AIS publications mention how dynamics at higher levels (e.g. national crop protection policy) can both enable and constrain innovation at the local level (e.g. Giller et al., 2011; Sims et al., 2012). However, the structural analysis of multi-level interactions is rarely part of current analytical frameworks within the crop protection literature and agricultural innovation systems literature. In terms of the geographical orientation, analysis demonstrates a more or less equal distribution of the four approaches to innovation over publications reporting on crop protection research in developed and developing countries.

5.3. Multi-actor

In spite of the observed increased frequency of participatory approaches and stakeholder involvement in research, this review shows that researchers generally remain to be seen as the developers of innovations and farmers remain to be perceived as the end-users or adopters of innovations. Examples of studies in which this is evident are Gijsbers and van Tulder (2011), Leitgeb et al. (2011), Mapila et al. (2012) and Raina (2003b). In the majority of these studies, farmers have little real influence on the research design. In many of the reviewed studies (notably the TT, AKIS and AIS publications), government extension services are allocated a central role in the crop protection system. In the TT publications, reforms of (national) agricultural research and extension systems are perceived as the engine for promoting innovation and development, and improving the diffusion of knowledge and technology (e.g. Ozcatalbas and Brumfield, 2010). Within the AKIS and AIS publications, extension services are seen as one among many actors and organisations that influence (enable or constrain) innovation in the crop protection system (e.g. Chandler et al., 2011). More recent AKIS and AIS studies apply a broader definition of crop protection actors by also including policymakers and private sector representatives, although the latter group remains weakly represented in the studies included in this review.

5.4. What comprises innovation in crop protection systems?

A large proportion of the systems-oriented publications in crop protection literature applies a technology-oriented approach to innovation. In these publications, innovation comprises the development of new crop protection technologies by – for example – research organisations or the agrochemical industry, and the (successful) linear transfer, adoption and diffusion of these crop protection technologies among the end users; farmers. AKIS and AIS publications describe innovation as a process, and successful innovation as the system's capacity to generate and respond to change (e.g. Nicholas and Durham, 2012). Le Bellec et al. (2012), for instance, discuss how an enabling environment for dynamic interactions between farmers, researchers and other actors can contribute to reducing current problems in crop protection systems, as well as to providing a solid basis for tackling future challenges. The majority of the AIS publications is 'optimisation-oriented'; i.e. exploring the optimisation of existing rules, chains of command or information flows within the crop protection system. For example, Probst et al. (2012) propose the need for stricter enforcement of crop protection policies. Only few of the crop protection publications categorised under the AIS approach are 'transformation-oriented'; i.e. questioning the need, necessity and impact of values, rules, chains of command or information flows in crop protection systems.

6. Conclusions

The objective of this systematic review was to explore the extent to which systems approaches to innovation are reflected in the crop protection literature and how such approaches are being used. Compared to technology-oriented approaches, systems-oriented approaches to innovation represent only a small part of the crop protection literature. Many of the systems-oriented crop protection publications continue to focus on the development, transfer, adoption and diffusion of technological innovations. A lot of publications use a sustainability perspective, in which there is attention for understanding biophysical, social–cultural and economic variability in relation to the use and performance of crop protection innovations. We conclude that more attention is needed for the institutional and political dimensions of innovation in crop protection systems. The majority of publications focusses on one level (e.g. crop protection at farm level or national level), without attention for multi-level interactions. Although the existing literature increasingly acknowledges the importance of involving multiple actors and stakeholders, researchers are still seen as the (only, or most important) drivers for innovation and farmers as adopters or end-users of innovations. The rethinking of the division of tasks and responsibilities between actors in the agricultural sector receives limited attention. Approaches focussing on structural transformations to enhance the overall crop protection system's capacity to generate and respond to change are discussed, but generally receive little attention.

Based on this review, we conclude that the potential of AIS approaches to analysing and addressing complex crop protection problems remains largely unexplored. AIS approaches can provide a useful framework in which synergies between technology- and systems-oriented approaches, discussed in this review, can be explored. It provides a starting point for understanding how multi-dimensional, multi-level and multi-actor dynamics influence innovation in crop protection systems. Within such a framework, researchers and other actors and stakeholders can work towards an enabling environment for more resilient crop protection systems. Although AIS approaches are increasingly part of research, policy and development processes, there is a need for research that can provide methodological guidance on AIS analyses, and reflections on the value and impact of AIS approaches in addressing crop protection, and other complex agricultural problems.

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