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Systems approaches to innovation in pest management: reflections and lessons learned from an integrated research program on parasitic weeds in rice

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Systems approaches to innovation in pest management: reflections and lessons learned from an integrated research program on parasitic weeds in rice

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This paper provides a retrospective look at a systems-oriented research program, on the increasing occurrence of parasitic weeds in rainfed rice in sub-Saharan Africa, to qualitatively assess merits and identify challenges of such approach. We gained a broad contextual overview of the problem and different stakeholders' roles, which enabled identification of entry points for innovations in parasitic weed management. At the crop level parasitic weed infestation is associated with poor soil fertility and water management. Farmers' infrequent use of inputs to control them was caused by various factors, ranging from fears of undesired side effects (agronomic) to a lack of quality control of products (institutional). Furthermore, there may be enough extension agents, but they lack the required training on (parasitic) weed management to provide farmers with advice, while their organizations do not provide them with the necessary means for farm visits. At even higher organizational levels we observed a lack of coherent policies on parasitic weed control and implementation of them. Merits and challenges of an integrated multi-stakeholder and multi-level research project are discussed.

Keywords: multi-disciplinary; trans-disciplinary; agricultural innovation systems (AIS); farmer participation; multi-stakeholder; crop protection

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1. Introduction

Systems approaches to pest management innovation have been advocated to complement purely curative – and often technology-oriented – interventions since the late 1990s (Lewis et al. 1997). A systems approach considers a specific crop protection problem not just as the outcome of a crop–pest interaction but also takes into account the context within which it is embedded. This implies considering multiple stakeholders, including farmers, extension and crop protection officers, agrochemical dealers and policy-makers. It also implies considering biophysical and socio-economic processes (e.g. pest life cycles, hydrology, communication, technology and knowledge transfer, marketing) and the formal and informal institutions or "rules of the game" that can include policies, regulations, patents and certifications (Hounkonnou et al. 2012). Such an approach would cover multiple integration levels, including plant, crop and farm level, and also community, region and country level. The hypothesis supporting the need for a systems approach is that a pest problem at the plant or crop level cannot be solved in a fundamental way if no enabling environment for addressing that pest outbreak at a higher integration level is created. In a systems approach, innovations are considered as outcomes of the combined advances of technological, social or institutional elements in the system that runs from the field and farm to the community, region and even higher levels (Leeuwis 2004), and of the interactions between different stakeholders in the agricultural sector (Hounkonnou et al. 2006; Klerkx et al. 2012).

Systems approaches are particularly useful as methodology for diagnosing and addressing complex problems with a capricious context that cross-cut different disciplines and integration levels and engage a variety of stakeholders (Pautasso & Pautasso 2010; Schut, Klerkx, et al. 2015; Schut, Rodenburg, Klerkx, Kayeke, et al. 2015; Schut, van Paassen, et al. 2014). The usefulness of systems approaches has become increasingly recognized not only by social scientists but also by natural scientists in fields such as crop science and applied ecology as a way to enhance the relevance and impact of science (Nederlof et al. 2007; Jordan et al. 2012; Hulme 2014; Runck et al. 2014; Smith et al. 2014). The systems approach is also appropriate for managing research efforts with an applied objective such as crop protection. However, a recent systematic review of the crop protection literature showed that, despite the clear potential advantages outlined above, truly systems-oriented approaches to crop protection problems, as well as robust assessments of them, are scarce (Schut, Rodenburg, et al. 2014). Crop protection problems and possible solutions to

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them have been studied using farmer-participatory approaches (e.g. Abang et al. 2007; De Groote, Rutto, et al. 2010), but have rarely been approached as multi-level and multi-stakeholder systems and are seldom studied in an integrated way and used to inform integrated pest management approaches. The only noteworthy exception we found is a study from Australia reporting on multi-stakeholder workshops focusing on integrated pest management (Norton et al. 1999). Published studies showing the value of integrated systems approaches to crop protection problems in developing countries, with generally weaker institutions and resource-poorer stakeholders, are not available (Schut, Rodenburg, et al. 2014).

In the PARASITE program,[1] a research collaboration between Wageningen University, Africa Rice Center and National Agricultural Research and Extension Systems from Benin, Cote d'Ivoire and Tanzania – starting December 2010 – an innovation systems approach was used to study parasitic weed problems in rainfed rice production systems. Parasitic weeds in rice can be considered a complex crop protection problem (Rodenburg et al. 2015; Schut, Klerkx, et al. 2015; Schut, Rodenburg, Klerkx, Kayeke, et al. 2015). The problem is embedded in a capricious context as it involves a multitude of stakeholders and organizations, is affected by a multitude of interactions across different integration levels (e.g. climate, soil, crop, farm, markets, policy) and is encountered in subsistence farming systems with rainfed and therefore risk-prone and uncertain crop production environments. Rice production in Africa is hampered by several technological, institutional, socio-cultural, political, economic and biophysical constraints (Seck et al. 2012). Weeds are one of the most important biological production constraints causing production losses conservatively estimated at US$1.45 billion, equating approximately half the current imports of rice into Africa (Rodenburg & Johnson 2009). With a minimum estimated annual production loss of US$391 million, parasitic weeds are estimated to be the cause of at least a quarter of these weed-inflicted economic losses (Rodenburg et al. 2014, 2015). The economically most important parasitic weeds in rice production systems are the obligate hemi-parasitic Witchweeds *Striga hermonthica* (Del.) Benth. (in West Africa) and *S. asiatica* (L.) Kuntze (in East Africa) and the facultative hemi-parasitic Rice vampireweed, *Rhamphicarpa fistulosa* (Hochst.) Benth (Rodenburg et al. 2010). Parasitic weeds primarily occur in rainfed agro-ecosystems in sub-Saharan Africa (SSA). These rainfed systems comprise roughly 74% of the total rice area and account for an estimated 66% of total rice production in the region (Diagne et al. 2013). Subsistence farmers with limited financial means and poor access to (quality) information and education are the most affected by parasitic weeds (e.g. Stringer et al. 2007).

In the case of parasitic weeds, informal interviews with rice farmers and nearby agricultural extension agents in Benin and Tanzania (August–September 2009), revealed that there were large time gaps between the first appearance of the problem, the identification of the parasitic weed in the field, and finally the development and dissemination of appropriate weed containment and prevention strategies on a crop, community and country level. This pattern is symptomatic for a sub-optimally functioning crop protection system. In response to these problems, the PARASITE program was designed to address challenges at several levels, and contribute to the development of a crop protection system that is better prepared for future outbreaks. The parasitic weed problem was investigated at the plant and crop level, the farm level, the farm household level and at the institutional level. The ultimate aim of this approach was to close the knowledge gaps in the fields of biology, ecology, economics and management of parasitic weeds in rice-based cropping systems in SSA, and to identify and facilitate the institutional innovations required to address similar emerging biotic production constraints in a timely manner. To the best of the authors' knowledge the PARASITE program represents the first study whereby the problem of parasitic weeds is approached in an integrated way, across different integration and administrative levels and involving multiple stakeholders. With the end of the project approaching, after 4 years of research, the central question of this retrospective paper is whether the participants perceived the merits ensuing from the application of a systems approach. For this reason, the paper synthesizes the lessons learned by project staff and participating stakeholders, and generates recommendations that result from this initiative. Specific questions that are targeted in this paper are: (1) Where and how does an integrated research approach contribute to broaden the problem analysis and to refine the solution? (2) Have we identified bottlenecks of the problem of parasitic weeds in rice, which would have remained undisclosed when using a less integrated approach? and (3) What can be done to further improve the efficacy of an integrated research project? With "integrated research" we refer to research at different integration levels (from the plant level to the country level) whereby scientists from different disciplines and stakeholders from different categories work together. Following definitions of Pohl and Hirsch Hadorn (2008), Tress et al. (2009) and Smith et al. (2014), integrated research is (1) inter-disciplinary when scientists from different disciplines within one science category collaborate (e.g. ecology, biology), (2) multi-disciplinary when scientists from different disciplines and multiple science categories work together (e.g. natural sciences, social sciences, humanities), and (3) trans-disciplinary when scientists from different disciplines and multiple science categories work together with stakeholders from different levels. The paper starts with an overview of the PARASITE program, including a synopsis of its underlying projects. Next, it systematically answers the above-outlined questions, mostly illustrated by concrete examples derived from the program.

2. PARASITE: an integrated research program

Because of interactions and interdependencies between factors, stakeholders and processes at the plant, crop,

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household, village and country level we hypothesized that only with an integrated approach one can explore effective and durable solutions to parasitic weed problems. The PARASITE program that emerged from this notion was designed as a composition of four interlinked projects that operate at different integration levels, cover different disciplines and involve a variety of stakeholders:

- Project 1: Understanding how host−parasite interactions for economically important parasitic weed species in rainfed rice in SSA are differentially affected by present and expected future environmental conditions.
- Project 2: Developing and disseminating locally adaptable and socially and economically acceptable strategies for prevention and damage control of parasitic weeds in rainfed systems in SSA.
- Project 3: Assessing socio-economic impacts and determinants of parasitic weed infestation in rainfed rice systems in SSA.
- Project 4: Evaluating and addressing the institutional organization and preparedness of extension and crop protection systems in SSA for emerging biotic constraints under future changing environments, using an innovation systems perspective.

The first three projects specifically focused on finding solutions for parasitic weed problems in rice production systems. Project 2 occupied a central position as it involved the development and evaluation of management strategies for dealing with parasitic weeds at the farm and field level. This required a sound understanding of the biology and ecology of the parasitic weed and the interaction of the parasite with the host (rice) plant, the focus of project 1. At the same time, the control measures needed to fit in the socio-economic environment the farmers operate in. The participatory development of management strategies thus also required knowledge on causes of adoption and rejection of previous (technological) innovations, the kind of insights gathered in project 3.

Rather than merely finding solutions for the parasitic weed problem in rice, the overall program had a wider scope. As the problem with parasitic weeds in rice had been picked up much too late by extension and crop protection services, an important objective was to render future crop protection services more proactive and effective such that newly emerging crop protection constraints could be identified in an early stage. Project 4 therefore complemented the program as it assessed the constraints and opportunities for institutional innovations required to effectively address current and future crop protection problems.

The first three projects were conducted by PhD students, whereas project 4 was conducted by a postdoctoral researcher. All projects were supported and supervised by a multi-disciplinary team. An additional activity included a desktop study on the importance of parasitic weeds in rice in Africa, including a global herbarium and literature review combined with spatial and economic modeling, carried out by senior scientists. Moreover, several surveys and experiments were conducted by MSc-level students. Several program workshops, at the start, mid-term and near the end, and frequent smaller (online and face-to-face) meetings were organized to achieve program coherence and stimulate integration and communications between the different projects.

3. Synopsis of the projects

3.1. Understanding host−parasite interactions and environmental effects

Insights in weed biology and ecology enable the design of effective control measures (Mortensen et al. 2000). While the biology of the most important *Striga* species was fairly well understood, basic information on *R. fistulosa* was still lacking at the onset of this project. During two seasons, 2012 and 2013, we conducted field observations on the ecological niches of *S. asiatica* and *R. fistulosa* in Kyela, a site in southern Tanzania where both species are present in the same agro-ecological and socio-economic environment, and confirmed these with controlled experiments in the greenhouse and vice versa. These observations included an assessment of the associated weed species' communities, soil fertility and texture of each habitat and the parasitic weed-free transition zone we identified between each habitat, as well as the range of favorable soil-water contents for each parasitic weed. We further conducted controlled experiments with *S. asiatica* and *R. fistulosa*, in greenhouses in Tanzania and the Netherlands, with the aim to compare the seed conditioning and germination requirements of obligate and facultative parasites of rice, to assess the effects of the parasites on host plant performance and to assess the effects of the host on the fitness of the parasites. Information so acquired added to our understanding of the ecology and environmental versatility of the species, in particular of the lesser known *R. fistulosa*, which forms the basis for better informed and prepared stakeholders.

3.2. Developing and disseminating locally acceptable management strategies

Farmer participatory approaches have been advocated for problem definition and technology development for pest problems in subsistence farming systems in Africa (Van Huis & Meerman 1997), and used previously, for instance, in the context of *S. hermonthica* management in maize in Kenya (De Groote, Rutto, et al. 2010). In the current project we interviewed local extension officers and rice farmers in one of the identified hot-spots for parasitic weeds in rice, in Kyela District (southern Tanzania). The interviews provided insights in the current level of understanding regarding the parasitic weed problem and were intended to identify possible locally originating or adopted management strategies already in use. Based on this, a selection of potentially suitable practices was tested in the field in researcher-managed on-farm trials (in a

S. asiatica-infested upland and a *R. fistulosa*-infested lowland field) during three cropping seasons, and evaluated by participating farmers. The trials not only contained promising control options, but were also used to verify drawbacks of alternative measures that were mentioned by farmers as obstacles to implementation. For the fourth and last season (December 2014 to July 2015), 50 volunteer farmers were grouped in 10 groups of five farmers each to test three component technologies of their own choice and one combination of these technologies against their own practice in one of the group members' field. Five such farmer-managed on-farm test plots were established this way in a *R. fistulosa*-infested zone and five in a *S. asiatica*-infested zone. During the season, two farmer exchange days were organized to assess the effectiveness of technologies and combinations and to get feedback from individual farmers through interviews on their experiences with them. Alongside these trials, farmer-participatory workshops were held, with 89 farmers in Kyela District (28 with *S. asiatica* problems, 28 with *R. fistulosa* problems and 33 with both *S. asiatica* and *R. fistulosa* problems), 30 *S. asiatica*-affected rice farmers in Morogoro Rural District and 30 *R. fistulosa*-affected rice farmers in Songea District, to assess farmers' knowledge and preferences concerning management strategies. Baseline surveys were carried out in hot-spots in Benin, Cote d'Ivoire and Tanzania in collaboration with project 3.

3.3. *Assessing socio-economic impacts and determinants of parasitic weeds in rice*

Insights in the effects of parasitic weeds on social and economic functioning of the farmer communities, and vice versa, i.e. the effects of the economic and social conditions on likelihood and severity of parasitic weed infestations, were unknown prior to this project. Production data, farmer perceptions of direct impacts and future levels of parasitic weed incidence and their preferences for management practices were gathered and field data on infestation levels and damage were collected. Farmer surveys were done in hot-spots in Benin ($n = 223$), Tanzania ($n = 201$) and Cote d'Ivoire ($n = 240$). Perceived social effects of parasitic weed problems at the field level (e.g. land use intensity and land use change), household level (e.g. schooling rates, gendered allocation of labor, financial resources) and community level (e.g. communal workgroups, access to land) as well as knowledge, preferences and adoption of management strategies were assessed.

3.4. *Evaluating the institutional dimension of parasitic weeds and crop protection systems*

In order to investigate why large time gaps may exist between the first appearance of a pest problem and the initiation of research and extension initiatives to address this constraint we analyzed the system's capacity to identify and address problems. We drew thereby on insights from agricultural innovation systems (AIS) thinking, an approach with increasing application in the context of better understanding complex agricultural problems in developing countries (Hall et al. 2001; Sumberg 2005; Ekboir et al. 2008; Amankwah et al. 2012; Klerkx et al. 2012). The AIS approach highlights the importance of adequate linkages and cooperation between heterogeneous stakeholder groups, from identifying, describing and explaining the problem to exploring, designing and implementing solutions. The lack of an operational methodology to conduct *ex-ante* AIS diagnostics led us to develop a toolbox for the Rapid Appraisal of Agricultural Innovation Systems (RAAIS; Schut, Klerkx, et al. 2015). RAAIS was developed and applied in Tanzania and Benin across the same six parasitic weeds hot-spots that were earlier selected for our research activities. The toolbox combines multi-stakeholder workshops, semi-structured interviews, questionnaires and secondary data analysis. Three multi-stakeholder workshops were held per country, with a total of 134 participants (68 in Tanzania and 66 in Benin) representing farmer organizations, NGOs/civil society organizations, private sector, government, and research and training institutes. The aim of the workshops was to identify and analyze constraints and opportunities for crop protection innovation, which should result in a coherent set of specific and generic entry points for innovations. Workshop data were validated and followed up with 107 individual semi-structured interviews with key informants from the different stakeholder groups (42 in Tanzania and 65 in Benin). In addition, in Tanzania a farmer ($n = 120$) and extension agent ($n = 30$) survey was conducted.

4. Discussion

4.1. *Where and how does an integrated research approach contribute to broaden the problem analysis and to refine the solution?*

An integrated research approach implies that actors from different scientific disciplines, as well as non-academic actors, work together, combining different integration levels, perspectives and factors. The assumption is that this will lead to more holistic insights and consequently to more relevant and realistic solutions to the problem at hand. To answer the above question, we provide examples derived from the PARASITE program.

By combining global public herbarium and (weed science) literature data with geographic information systems, ecological knowledge and economic data and modeling, we are now able to provide best-bet estimates of the economic importance of parasitic weeds in rice in Africa. The herbarium and literature data provided information on the geographical distribution of different parasitic weed species (e.g. Mohamed et al. 2001; Rodenburg et al. 2014, 2015). We found out that *Striga* species are spread over 33 African countries that produce rice in the rainfed uplands where these species can be encountered. *R. fistulosa* was found in at least 32 countries that produce rice in rainfed lowlands where the species thrive. The next step was to overlap these distribution maps with

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national or regional maps of rainfed rice areas. Combined with knowledge on the environmental preferences of each weed, obtained from project 1 (e.g. Kabiri et al. 2015), and figures obtained on their appearance, frequency, infestation rates, yield losses and the socio-economic factors affecting these variables obtained from project 3 (e.g. N'cho 2014), we can estimate a stochastic impact of parasitic weeds on rice production, using a diverse set of modeling techniques. Based on a first raw model, the maximum annual regional economic losses caused by *R. fistulosa* in rice were estimated at US$569 million, while for *Striga* spp in rice these were estimated at US$169 million.

Findings from farmer surveys (project 3) corroborate findings from our ecological studies (project 1) and agronomic work (project 2). The likelihood of infestation by *R. fistulosa* is higher on poorly fertile soils and fields located in the valley bottom and it is reduced through management practices such as late sowing and the application of medium-rate fertilizer (N'cho, Mourits, Rodenburg, et al. 2014). Based on pot experiments combined with field measurements and observations, Kabiri et al. (2015) concluded that the valley bottoms are the preferred habitat for *R. fistulosa* and that the soils in these valley bottoms can be characterized as poor in terms of fertility. An earlier study based on pot experiments, by Rodenburg et al. (2011), showed that *R. fistulosa* can indeed be reduced by the application of inorganic fertilizers leading to increased (chemical) soil fertility. However, only by broadening our perspective and zooming out from the plant level to the farm household level, we were able to understand the social repercussions of these findings. N'cho, Mourits, Rodenburg, et al. (2014), for example, recorded higher infestation rates on rice plots managed by female-headed households than on plots managed by male-headed households. A more in-depth analysis revealed that 61% of these female-managed plots were located in the valley bottom. From previous work it was indeed established that population pressure often drives farmers to marginal land or fields in less favorable positions on the upland–lowland continuum, such as the valley bottom, and often women are the recipients of the more marginal fields characterized by low soil fertility and weed problems (Demont et al. 2007). The combined insights in economic impacts, ecological and social relations, can be used to communicate the problem more clearly and more convincingly to extension services, policy-makers – at regional and national levels – and donors of future research for development endeavors. The finding about the relation between parasitic weeds and poor soil fertility (projects 1 and 3) formed the basis for farmer-participatory development of soil fertility-based management strategies to combat these weeds (in project 2).

In the process of reviewing scientific literature on systems approaches to innovations in crop protection (Schut, Rodenburg, et al. 2014), it proved challenging for the PARASITE researchers from different disciplinary backgrounds to align perceptions and conceptualization of "what are systems approaches to innovation?" It turned out that the natural science researchers and the social science researchers had very different perceptions and interpretations about this. Natural science researchers considered systems as functional units with clear boundaries (e.g. the photosynthesis system within a plant, or a plant production system as a population of plants within an agricultural field) and bio-physical modeling or factorial experiments as approaches to understand mechanisms and (bio-physical) processes and identify elements that can be improved (e.g. through engineering) to innovate those systems. Social science researchers had much more attention for the contextual embedding of a certain study topic (e.g. a pest problem) and no or less attention for technical details and biophysical mechanisms. They considered systems as a network of social and institutional relations and functions of actors or stakeholders associated to a specific context (e.g. a pest problem), with no clear boundaries. Systems approaches to innovation are seen by social scientists as multi-stakeholder/actor processes and research activities are hence geared towards understanding these social relations and functions with the aim to improve the communication and collaboration between the stakeholders/actors relevant to achieving innovation to solve the (pest) problem (Schut, Rodenburg, Klerkx, Hinnou, et al. 2015).

Together, a research framework was developed that guided the analyses of how different ways of thinking about systems approaches to innovation are reflected in the crop protection literature. One of the main conclusions of the review was that crop protection is often about exploring and optimizing technologies within the farming system, rather than about fostering structural transformations of the agricultural (innovation) system. This integration of different disciplinary expertise and views helped us to improve the implementation of research methods and the interpretation of the outcomes. The most obvious example is the generation of farmer questionnaires that were used across projects 2, 3 and 4. For this we worked in concerted action with project staff of different disciplines and this helped in improving the relevance of the questions and therefore the quality of the questionnaire. For the social scientists (six program partners), it proved important to better understand some of the technical dimensions of the problem at hand (parasitic weeds) as well as the solutions. This helped them to improve the logic (separate causal from non-causal relations) and the relevance (separate direct from indirect factors) of the questionnaire and the interpretation of the data deriving from the questionnaire. For the plant and crop scientists (nine program partners) it proved worthwhile to get a feel for the socio-economic and institutional context of the problem and to make sure the questions asked were understood by the farmer and interpreter. Social scientists have more experience with survey work and they follow certain methodological rules to ascertain that questions are unambiguous and to triangulate the data. This proved very useful for improving the quality of the questions designed by natural scientists. Our experience supports the conclusion by De Groote, Vanlauwe, et al. (2010) that for research on

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farm level, in order to conduct relevant research resulting in useful and feasible solutions to resource-poor farmers, agronomists need to collaborate with economists.

By implementing a newly developed method (RAAIS), challenges, constraints and opportunities for innovations related to parasitic weeds in rainfed rice production systems were explored, in project 4, through an integrated analysis of different problem dimensions, interactions across levels, and the needs and interests of multiple stakeholders. The uptake and impact of solutions or management strategies is often determined by the technological effectiveness or economic feasibility of a solution as well as by the way the process towards identifying or developing that solution was organized (i.e. in isolation or together with stakeholders). In the PARASITE program, a transdisciplinary approach ensured that solutions generated by the team were robust, applicable and locally adapted. For instance, the observation that parasitic weeds are associated with poor soils (project 1 and project 3) combined with the notion that affected farmers are among the poorest and most disadvantaged and cannot afford expensive inputs such as mineral fertilizers (project 3), we discussed with farmers what alternative (low-cost and available) inputs would be available to raise the soil fertility of their fields (project 2). From these researcher−extension−farmer discussions it became apparent that cattle manure and rice husks were freely available. While farmers were reluctant towards the use of manure, as they were expecting this would increase ordinary weed infestation, we agreed to test these two readily available and low-cost soil fertility amendments against mineral fertilizers and in combination with reduced doses of such fertilizers. From three seasons of farmer participatory trials the combination of rice husks and reduced doses of mineral fertilizer emerged as the most effective and preferred one. Parasitic weed levels were reduced and rice yields improved, while the costs were affordable. Farmers then picked this solution to test it against their own practice in their own fields. These on-farm try-outs were carried out in 10 farmer groups, each of which was led by the more progressive and innovative farmers that emerged during the previous three seasons.

The RAAIS identified institutional and political prerequisites that could provide an enabling environment for the broader dissemination of such strategies and for raising awareness of the problem. By discussing the problem and context of the problem with different stakeholder groups, previously unknown bottlenecks were identified. For instance − at national and regional levels − the lack of education and training of extension, sub-optimal interactions between stakeholders, the lack of coherent policies and implementation of them, and the weak structural allocation of human and financial resources for extension services, emerged as constraints (Schut, Rodenburg, Klerkx, Hinnou, et al. 2015). These bottlenecks could consequently be taken into account when developing solutions. For instance, a previous project funded by DFID targeted the problem of *S. asiatica* in rice by involving schools in teaching about such problems and how to deal with them (Riches et al. 2005).

Figure 1 visualizes the PARASITE program's (expected) steps from the start to the finish (and beyond). The start is demarcated by the first superficial identification of the problem ("Parasitic weeds in rice are being increasingly observed"), followed by the identification of multiple facets of that problem ("Farmers do not know how to address the problem" and "Extension and crop protection services are unaware, researchers lack conclusive insights") and the more fundamental underlying causes ("Suboptimal communication between stakeholders, laws and regulations not appropriate or not implemented, lack of strategies, lack of resources"). This clarifies what is lacking to solve the problem of parasitic weeds (i.e. "Insights in biology and ecology, and technical and institutional innovations") and through the proposed and implemented approaches (i.e. "Multi-stakeholder workshops, interviews and surveys" and "Surveys, field observations and pot experiments; farmer-participatory tests of weed management strategies") what measures are concretely needed (i.e. "Policy priorities; training and education on weed prevention; stakeholder communications" and "Locally adapted and acceptable management strategies based on ecological principles") and how this can feed into the next steps (i.e. through "Up-scaling and out-scaling through partner networks and communications"). A connecting arrow between "Locally adapted and acceptable management strategies based on ecological principles" and "Policy priorities; training and education on weed prevention; stakeholder communications" underlines that the insights derived from the field-based development of parasitic weed management strategies feed into the development of training curricula and awareness raising (e.g. through videos), underpinning the integrated approach of the project. The dashed arrows then indicate the contribution, either directly or indirectly, to solving the initial problem, i.e. the increase of parasitic weeds in rice. The up-scaling of policy recommendations should lead to an enabling policy environment, which in turn facilitates the out-scaling of the adapted and acceptable strategies. The box "Enabling policy environment" is shaded differently to indicate that this cannot be targeted directly by our program. To trigger the processes in the final steps, prior to conclusion of the PARASITE program we will organize multi-stakeholder workshops, bringing together the most important stakeholders in each intervention country, to discuss the results of our work as well as the way forward.

4.2. *Have we identified bottlenecks of the problem of parasitic weeds in rice, which would have remained undisclosed when using a less integrated approach?*

A limited number of previously published peer-reviewed papers from other scientific fields support the view that many contemporary issues can best be studied through integrated research (e.g. Pautasso & Pautasso 2010), and that such an approach results in insights that would not have been obtained with a more disciplinary approach (e.g. Merz et al. 2006). Insights gained through the PARASITE program clearly show the merits of an integrated approach. In

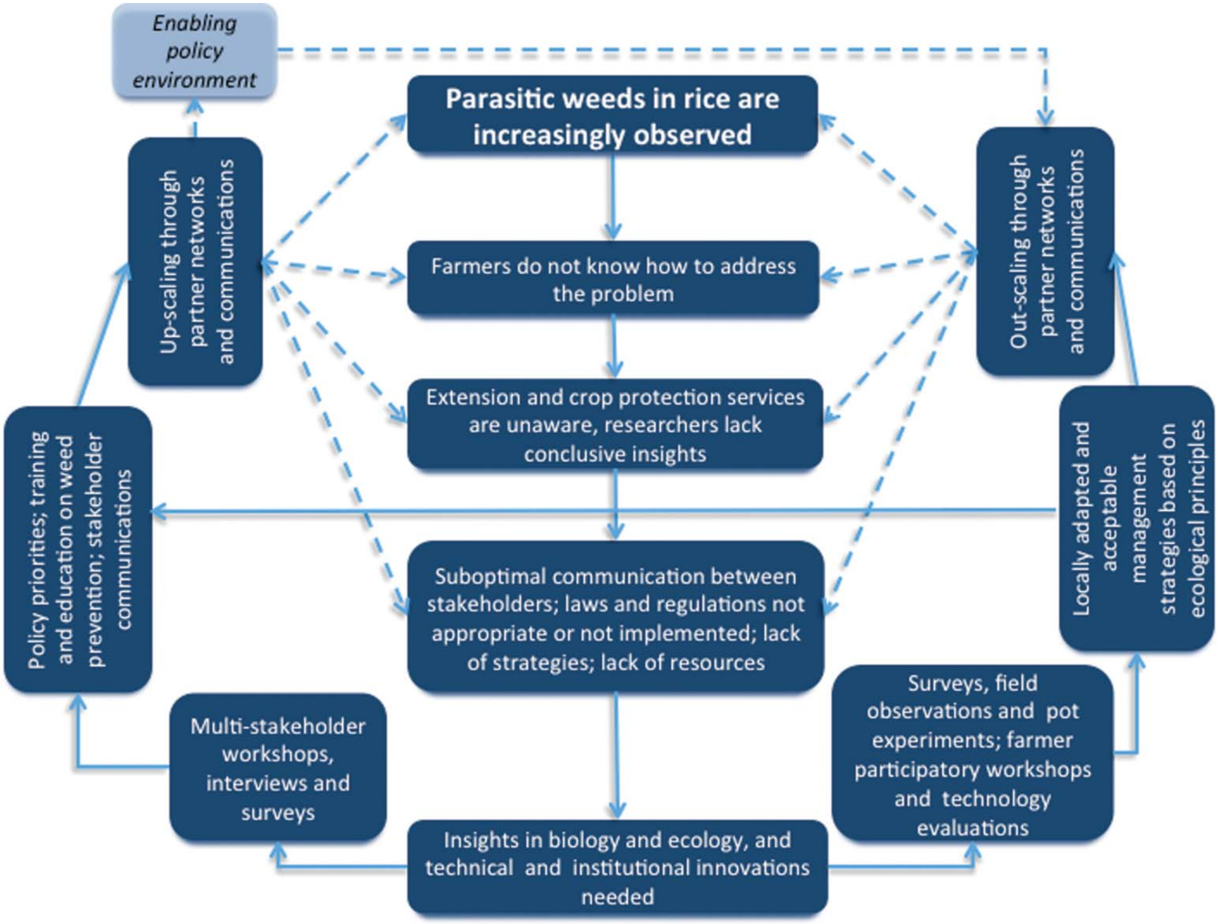

Figure 1. Schematic representation of the PARASITE program's stepwise evolution, whereby solid arrows indicate PARASITE program steps and dashed arrows indicate how products and outcomes of the program can address the initial problem at hand.

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the grant proposal of the program we wrote: "Farmers generally lack the knowledge and means to effectively address parasitic weed infestations. Extension services are not always aware of the actual extent of the problem and they are often unable to backstop farmers with adequate solutions." The project enabled us to conclude that the "inability" of the extension services is part of a more structural problem. In project 4, we observed limited attention for weed prevention and control in agricultural research in Tanzania as a consequence of the national and zonal agricultural research priorities outlined in strategic plans. A *Striga*-control policy was developed by the Ministry of Agriculture but never implemented due to lack of operational resources. Universities and technical training curricula of extension officers paid little attention to weeds in general, or parasitic weeds in particular (Schut, Rodenburg, Klerkx, Kayeke, et al. 2015). This corroborated findings of project 3 showing that adoption of control or prevention strategies is a function of farmers' access to information and training in weed management (S. N'cho, personal communication). The RAAIS interviews however identified a number of researchers at the university and the national research institutes that were highly motivated, or triggered by our research, to pay more attention to parasitic weed problems in rice in future research and training activities. A second problem we identified in project 4 is that, although country-wide the extension staff in Tanzania had been increased recently, this increase was not associated with an increase in funds and means, such as extension materials, training and transport. The lack of funds and means seriously hampered extension staff to function well. If the problem had not been analyzed across multiple stakeholders and using an integrated approach, linkages between such bottlenecks would not have been revealed and confirmed.

A barrier towards solving the problem of parasitic weeds is the apparent reluctance of farmers to use certain inputs (e.g. fertilizers). During workshops and interviews, it became apparent that this was partly resulting from contradictory advices to farmers by – for example – researchers, extension officers and development organizations. An example of the latter is the case where a government project promoted the use of inputs in rural areas while a donor project promoted organic agriculture practices in cacao cropping systems with negative advices on the use of inorganic fertilizers. As a consequence of the latter, many farmers who were reached by the donor project started to abandon the use of mineral fertilizer, also in other cropping systems than just cacao. In the PARASITE program work, we identified multiple additional reasons why farmers in Kyela (Tanzania) are reluctant to use agricultural inputs:

- Institutional; the lack of quality control of agricultural inputs was mentioned as a constraint. The adulteration of crop protection chemicals, fertilizers and seeds often prevent farmers from investing in such products.
- Economic; purchasing power of farmers is low.
- Socio-cultural; farmers are concerned that the use of improved varieties will contaminate the aromatic qualities of the local rice varieties.
- Political; frequent changes and incoherence of agricultural policies create confusion and lead to unstable market conditions and fluctuating prices.
- Agronomic; farmers may be afraid for undesired side effects to the crop, e.g. higher weed infestation with the use of cattle manure as soil fertility amendment.

Evidently, there is a variety of reasons why farmers are hesitant to use agricultural inputs. Being aware of these perceptions is important, as it allows the research team to address these aspects in their research. The latter example for instance already became clear at the onset of our work, when we asked farmers in Kyela District in informal interviews ($n = 89$) what they know about the control of parasitic weeds. As previously explained, they indicated that cattle manure can be used for this objective but that they do not use it because of its stimulating effect on ordinary weed infestation. This has led to the design of one of the farmer participatory field experiments conducted in project 2, whereby we test with farmers whether their hypotheses hold or not. The idea was that if the hypothesis would be rejected, i.e. if cattle manure would decrease parasitic weeds without increasing ordinary weeds, we would be able to unleash a suitable and readily available control option (i.e. cattle manure), thereby enhancing the basket of options for farmers. Preliminary results seem however to confirm the farmer hypothesis (Kayeke et al. 2013).

4.3. *What can be done to further improve the quality of an integrated research project?*

Through the PARASITE program the participating natural and social scientists gained a general better understanding of the context of parasitic weed problems and crop protection problems. In line with findings from Jabbar et al. (2001), we conclude that much of the agronomic research is focused on technology generation and adoption at farm level without recognizing that addressing administrative or more structural (institutional) levels may have higher leverage (e.g. by improving training, awareness, communications). On the other hand, social scientists enhanced their methodological portfolio, either by combining their usual (more) qualitative and associative (e.g. snowball) approaches with more structured and quantitative (objectively measurable) methods or by expanding from surveys to more experimental methods. Social scientists also benefited from working on a concrete problem that needs a concrete solution. In other words, it helps to frame and focus research contributions, and operationalize concepts (such as AIS) in such a way that they can contribute to the development of effective intervention strategies *ex-ante*.

We learned that at each integration level one should zoom in or out to consider the specific or wider context and to critically assess whether solutions proposed are relevant and even whether the problem itself is relevant. At the plant level, parasitic weeds have a dramatic impact (up to death of the host plant) whereas at the farm level, parasitic weeds are only one component of a set of constraints. At the level of extension services it might be overlooked or ignored and at the level of agro-chemical-industry, where overarching issues like soil fertility and weeds are targeted, it may not be a specific issue at all. The solutions to the problem found at plant level (e.g. specialized varietal resistance mechanisms or herbicide formulas) may not be accessible or available at the level where they are needed. Farmers consider trade-offs between management of their parasitic weed problem and other problems, based on cost−benefit analyses, as they often have limited resources. Second, due to market failures or a lack of interest by industries to develop and deliver certain technologies, the solutions found at crop or plant level may not even be, or become, available to farmers (e.g. Demont et al. 2009; Oude Lansink 2011). Recognizing these market failures, as well as state and community failures, we are further analyzing (under project 4) the incentives (and disincentives) of private, public and community actors to provide specific products and services for the prevention and control of parasitic weeds.

One of the obvious challenges encountered during the program concerns the trade-off between integration and specialization and, related to that, the balance between an apparent time-efficient and output-oriented, mono-disciplinary approach and a slower and higher risk entailing trans-disciplinary approach. Truly integrated research, whereby non-academic stakeholders and scientists from multiple disciplines come together and make an effort to understand each other and cross their own subject boundaries with the aim to create new insights and knowledge (as formulated by Tress et al. 2009), implies a certain risk of failure and consequently a loss of time. The risk entails that the project objectives are not achieved because of misunderstanding of project partners (stakeholders and scientists), due to different jargon and different integration or abstraction levels of thinking. Overcoming such problems obviously takes additional time. Current day research funding and administration, with clear and rather strict time frames, deadlines and publication requirements, may not encourage scientists to undergo such a lengthy and risky process (Bardsley 1999; Roux et al. 2010; Botha et al. 2014; Schut, van Paasen, et al. 2014). The envisaged added value of such an approach, e.g. adaptation to changing context and stakeholder needs and interests, more space for learning − should however lead the decision to embark on it. Donor agencies can play an important role in stimulating these approaches, by putting these aims − of adaptation and learning processes − high at their agendas. In our PARASITE program the balance

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between disciplinary integration and output-oriented work was sometimes difficult to maintain. This was perhaps partly the outcome or the cause of the narrow interfaces between the different projects. There are obvious direct links between the plant sciences project (project 1) and the agronomy project (project 2), and between the agronomy project and the two social sciences projects (project 3 and 4), but the links between project 1 and project 3 or 4 were virtually absent. This is perfectly acceptable and shows that there are limits to the integration of disciplines. Natural sciences are an integral part of agronomic knowledge and, hence, indirectly impact broader levels of research through their overall contribution to a better understanding of the natural environment in which farmers operate. Moreover, just the identification of links is no guarantee that interaction and integration of disciplines really occur. Trans-disciplinary research projects require supervisory teams with members of relevant and representative disciplinary and stakeholder categories that are willing and able to get out of their disciplinary comfort zone and engage with each other and with other stakeholders. Individuals in such teams should try to understand members of other disciplinary backgrounds and be willing and able to share and explain their own perspective and expertise in a way that facilitates the necessary dialogue that should lead towards synergy. To avoid that individual project members continue working merely within their own, usual disciplinary boundaries, the period of planning and preparation of an integrated project should be enhanced. This preparation time should be used for multi-disciplinary and multi-stakeholder discussions coming to construction of a clear framework and work plan, e.g. by using problem trees, stepwise planning of activities and (*ex-ante*) impact pathways, in order to go beyond multi-disciplinarity and make the project truly trans-disciplinary. This may also lead to an adaptation of the research agenda, as far as this is possible, once the research evolves. In fact, trans-disciplinarity will only be truly beneficial when interaction between disciplines and between researchers and other stakeholders is guaranteed in all stages of the research project (i.e. defining objectives, implementation of methodologies and analysis and interpretation of outcomes). Finally, for a fair assessment as to whether an integrated approach should be preferred over a more mono-disciplinary approach, the additional costs should be taken into account and compared to the available budget. In the case of the PARASITE program the total research costs were approximately US$340,000 of which 27% was used for project 1, 40% for project 2, 20% for project 3 and 13% for project 4. Hence, while our experience points out that project 4 has been particularly instrumental for the actual implementation of the systems approach, this was also the least expensive of the program components. However, essential additional expenses, made to ensure integration of the different program components, involve communication costs (i.e. workshops, telecommunication and traveling). These are estimated to be around US$90,000. If the PARASITE program is exemplary, from this we can conclude that on a total project budget (in our case US$430,000, excluding salary costs) roughly one-third may be required to pursue an integrated systems approach.

5. Conclusions

By using an integrated systems approach to innovation we have identified and confirmed a number of bottlenecks to the solution of the problem of parasitic weeds in rice, at different stakeholder and integration levels. We conclude that the approach is instrumental for applied subjects such as crop protection. A systems approach proved essential for the assessment of the extent and causes of the actual crop protection problem as well as for finding solutions. We found that problems almost always affect agronomic, economic and social issues and cut across different integration levels and multiple stakeholder groups. Upon identification of a problem at any level (e.g. the crop level) one should zoom in and out to consider the specific or wider context and to critically assess whether the problem should be prioritized and whether and how solutions proposed resonate with the needs and interests of different groups of stakeholders. This process can only be conducted by a team consisting of closely collaborating researchers with different disciplinary backgrounds that, in turn, closely collaborate with other stakeholders representing multiple levels. The use of different disciplinary approaches, tools and methods also provided broad-based evidence on causes of the problem or entry points for innovation to address them. This, in turn, may help to strengthen recommendations for improved management of complex crop protection problems, and to align with stakeholders that can promote or implement solutions to address these.

We found that there are several challenges to operationalizing a systems-oriented and trans-disciplinary program. In order to ensure that trans-disciplinary research efforts succeed, members of research teams should be willing to understand and communicate with members of other disciplinary backgrounds, strive to share and explain their own perspectives, and collaborate closely with different groups of societal stakeholders. Participatory identification and planning of the different steps and activities, well before the actual implementation, is a precondition for a successful integrated research program. Furthermore, an important policy implication is that funding agencies should install a degree of flexibility into their funding schemes to adapt research agendas to emerging needs from stakeholders in a changing context, as well as allowing sufficient time for trans-disciplinary research to become effective.

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Note

1. PARASITE stands for: Preparing African Rice Farmers Against Parasitic Weeds in a Changing Environment; www.parasite-project.org

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