Chapter 3
Cover Crops in Agrosystems: Innovations and Applications

Johannes M.S. Scholberg, Santiago Dogliotti, Lincoln Zotarelli, Corey M. Cherr, Carolina Leoni, and Walter A.H. Rossing

Abstract Cover crops can reduce the dependence of farmers on agrochemicals while enhancing overall agrosystem's performance. However, the inherent complexity of cover-crop-based systems hampers their adoption by conventional farmers. Therefore, special management skills and alternative research and technology transfer approaches may be required to facilitate their adoptive use by conventional farmers. We propose that development and adoption of suitable cover-crop-based production systems may require the use of an "innovation framework" that includes (1) identification of system constraints, (2) analysis of system behavior, (3) exploration of alternative systems, and (4) system design and selection. We describe case studies from four regions of the Americas (Florida, USA; Paraná and Santa Catarina, Brazil; and Canelones, Uruguay) that illustrate the relationships between this innovation framework and the development and adoption of cover-crop-based production systems. Where successful, development and adoption of such systems appear to relate to a number of attributes including (1) active involvement by farmers in

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J.M.S. Scholberg (✉) and W.A.H. Rossing
Biological Farming Systems, Wageningen University, Post Box 563, 6700 AN,
Wageningen, The Netherlands
e-mail: johannes.scholberg@wur.nl

S. Dogliotti
Facultad de Agronomía, Universidad de la República, Avda. Garzón 780, Código Postal 12900,
Montevideo, Uruguay

L. Zotarelli
Agricultural and Biological Engineering Department, University of Florida, 234 Fraziers-Rogers
Hall, Gainesville FL32611, USA

C.M. Cherr
Department of Plant Sciences and Graduate Group in Ecology, University of California,
Davis, CA95616, USA

C. Leoni
Instituto Nacional de Investigación Agropecuaria – Estación Experimental Las Brujas,
Ruta 48 km 10 Código Postal 90200, Rincón del Colorado – Canelones, Uruguay

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research and dissemination programs; (2) integration of cover crops into production systems without net loss of land or labor resources; (3) informing farmers of the (direct) benefits of cover crop use; (4) provision of multiple benefits by cover crops, (5) sufficient access to information, inputs, and technologies required for cover crop use; and (6) provision of skills and experience necessary to manage cover crops effectively. Where these attributes are absent and failure to innovate has prevented development and adoption of cover-crop-based systems, policy initiatives to reward farmers for ecological services provided by cover crops may be required.

Keywords Cover crops • green technologies • system analysis • innovation • adoption • sustainability • Americas • green manure • living mulch

Abbreviation

SOM	soil organic matter

3.1 Introduction

Cover crops are extensively used to provide a wide array of services (Scholberg et al. 2009). In this review, we do not distinguish between specific applications such as their use for enhancing soil fertility, e.g., green manures, and cultivation techniques by which cover crops are grown simultaneously with commercial crops, e.g., live mulches. We therefore use the term "cover crop" in its broadest context instead.

Historically, cover crops have been an integral part of agricultural production systems (Scholberg et al. 2009). Technological innovations have greatly enhanced agricultural productivity over the last 60 years, but have also eroded many traditional techniques used to sustain inherent soil fertility – including the use of cover crops (Altieri 2002). During this period, many farmers throughout Latin America were caught in cycles of unsustainability related to overexploitation or pollution of water resources, soil erosion, loss of inherent soil fertility, increasing impacts of weeds and pests on crop yields, decreasing agricultural commodity values, and increases in external input prices. Local producers often responded to decreasing family income by intensifying their production (Dogliotti et al. 2005). Typically, this resulted in a shift toward cash crops, increased use of marginal lands, and greater dependence on external capital and labor and production inputs. This process favored further marginalization of local production systems (van der Ploeg 2008; Dogliotti et al. 2005; Cherr et al. 2006b) and saw many farmers and their families leave agricultural production and rural areas altogether. Increased global demand of crops for animal feed concentrates and biofuels has further intensified pressure on land resources (Corral et al. 2008). Although such production systems may generate local income and employment, these short-term economic benefits do not offset the loss of the long-term agricultural production capacity and human capital of local agricultural communities. Moreover, with current concerns about food security, global warming, and demands for a broader range of agricultural services, unsustainable resource exploitation is highly undesirable. Therefore, there is a need for more sustainable production options and more effective use of local or renewable resources (van der Ploeg 2008; Cherr et al. 2006b). Within this context, cover crops may once again become a cornerstone of sustainable agricultural systems (Scholberg et al. 2009). However, the complexity of cover-crop-based systems combined with the need to maintain reliably high crop yields requires the use of system analysis tools and active engagement of end-users (Shennan 2008; Cherr et al. 2006b). Involvement of the main stakeholders is particularly important, since any intentional change in production systems is always a result of changes in human conduct and therefore requires an individual and collective learning process (Leeuwis 1999). Moreover, solutions to complex problems do not come as "instant technology packages." Rather, they need to be designed within its context of application with the direct involvement of farmers at all stages of the process, from diagnosis to dissemination (Leeuwis 1999; Masera et al. 2000). This is the only way to ensure relevance, applicability, and adoption of such innovations. Thus, technological innovations such as improved use of cover crops must be explored more efficiently, while farmers must be allowed to more effectively contribute to technology development and transfer, thereby fostering successful and sustainable development (Rossing et al. 2007). Thus, the scope of this chapter is to

1. Provide a conceptual framework for innovation of cover-crop-based systems
2. Contextualize the components of this innovation framework as related to current cover-crop research and development strategies, with emphasis on system analysis tools
3. Describe innovation and technology transfer processed of cover-crop systems in several regions in the Americas

3.2 A Framework for Innovation of Cover-Crop-Based Systems

As biological organisms, cover crops interact with many aspects of a cropping system and its environment. The use of reductionist approaches, small-plot studies, and short-term research is common in agricultural science but may be poorly suited for development and evaluation of suitable cover-crop management strategies (Cherr et al. 2006b). Despite the large number of research and review publications centered on cover crops over the past decade, a conceptual framework and a systems' perspective that critically evaluates cover crops is lacking. Systems research uses an interdisciplinary approach to design and analyze agroecosystems functioning at different spatiotemporal and qualitative scales (Malézieux et al.

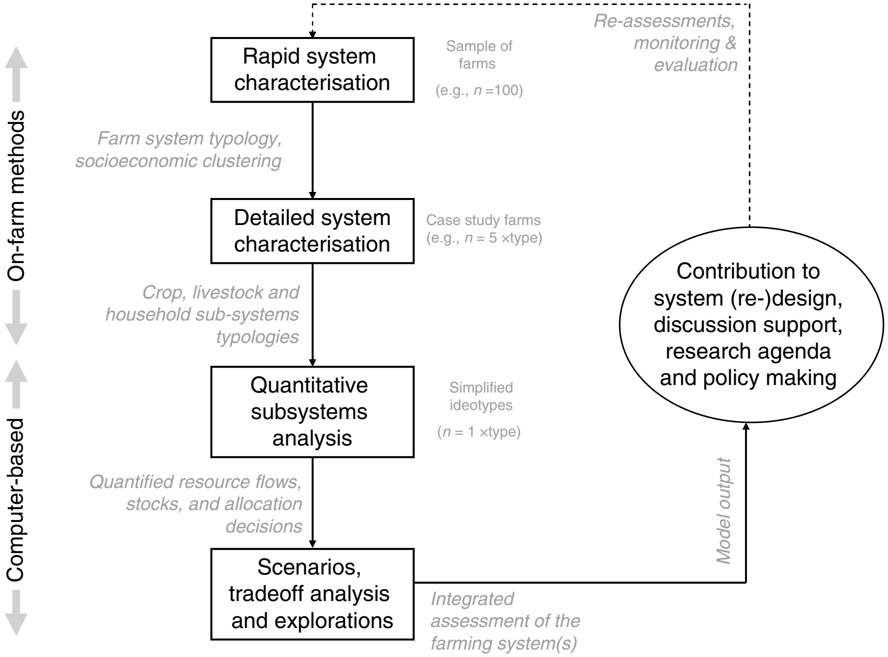

Fig. 3.1 Consecutive steps during farm analysis showing the complementation of both participatory and computer-based exploration and optimization approaches (Tittonell 2008)

2009; Shennan 2008; Drinkwater 2002). The underlying premise of system analysis and design is the use of cyclic knowledge development requiring active involvement from all key stakeholders. Ideally, this framework complements conventional research approaches, as shown in Fig. 3.1 (Tittonell 2008; Rossing et al. 2007). It includes the following:

1. Characterization and diagnosis of constraints: Description of the biophysical and socioeconomic system and defining constraints
2. Analysis of system behavior: explanation of the system behavior in terms of the constraints. The design of such a research may involve an initial assessment of native agricultural systems and models of ecological interactions (Shennan 2008; Altieri and Nicholls 2004)
3. Exploration of alternative systems: For example, generating different crop rotations and management practices either in reality or via simulation
4. Design of alternative system: Development or utilization of more efficient, profitable, or sustainable systems (i.e., via the use of trade-off analysis, model simulations, and optimization; see Fig. 3.1)

We emphasize that each component of the innovation framework is a process rather than an event, and there may be much overlap among the components. For example, integrating system analysis and design with applied field research and modeling techniques allows improved assessment of system constraints, explanation of behavior, and exploration of alternatives (Tittonell 2008). Within this context, field studies and data collection should be structured in such a manner that they can be used for calibration of simulation models and verification of model performance (Hasegawa et al. 1999). Such models, in turn, can then be used to explore more sustainable development options (Selaya Garvizu 2000).

We also explore the fourth component (design or selection of a system) by using the vehicle of technology development, adaptation, and transfer – which obviously overlaps the other three components. Nonetheless, we believe that the innovation framework we are proposing is a powerful approach for the development of viable cover-crop-based production systems.

3.2.1 Characterization and Diagnosis of Constraints

We organize the constraints on cover crop systems into three broad categories: biophysical, socioeconomic, and information and technology constraints. The categories are not necessarily mutually exclusive. We also briefly examine solutions to some of these constraints, which involve further steps in the innovation framework we are suggesting.

3.2.1.1 Biophysical Constraints

Although the use of cover crops is perceived to enhance production and provide a myriad of services, their adaptation by conventional farmers in North America has been slow (Sarrantonio and Gallandt 2003). The key issue may include the additional cost (in terms of land, labor, and inputs), the complexity of cover-crop-based systems, the lack of pertinent information, and the uncertainty of release patterns from cover-crops residues, and the lack of secure land tenure (Cherr et al. 2006b; Sarrantonio and Gallandt 2003; Lu et al. 2000). Since cover-crop-based systems depend on biological and ecological processes, this makes their management more complex when compared with the use of synthetic fertilizers. Most farmers are poorly equipped to take the economic risk associated with experimentation and exploration of suitable cover-crops technologies (Weil and Kremen 2007; Cherr et al. 2006b).

For example, severe yield reduction can occur when increased plant competition results from live mulch or incompletely killed cover crops (Hiltbrunner et al. 2007; Teasdale et al. 2007; Madden et al. 2004). Without adequate precautions, cover-crop residue may also interfere with soil cultivation, reduce subsequent crop seed germination (owing to poor soil–seed contact), delay planting operations (since residues need some time to decompose/die), harbor pests and diseases that attack subsequent crops (if the cover crop and subsequent crop host the same pests or diseases), decrease initial crop growth or delay crop maturity (owing to N immobilization, allelopathy, plant competition, or reduced soil temperatures), or reduce soil water availability (Peigné et al. 2007; Sustainable Agricultural Network 2007; Teasdale et al. 2007; Weil and Kremen 2007; Avila 2006; Cherr et al. 2006b; Sarrantonio and Gallandt 2003; Abdul-Baki et al. 1996, 1999; Masiunas 1998; Creamer et al. 1996). Poor synchronization of N release from decomposing cover crops and N uptake by subsequent crops will also result in high N losses (Cherr 2004).

However, if researchers become aware of these issues, then it is often possible to address them through redesign of the cover-crop system. In an example with vegetable crops, use of cover crops combined with zero-tillage reduced initial growth of vegetable crops and prevented growers from targeting the most profitable market windows. Once growers and researchers communicated about the problem, they identified a solution through the use of strip tillage. Such adaptive learning and innovation cycles are critical and therefore will be discussed in more detail in a subsequent section.

3.2.1.2 Socioeconomic Constraints

Technological development has often been perceived as a task of research institutions that subsequently transfer solutions to farmers. Unfortunately, this “top-down” approach frequently fails because it does not adequately include local socioeconomic and environmental conditions in the process of development (Anderson et al. 2001). On-station researcher-managed studies favor highly controlled conditions and research that may not be relevant to growers unless they are actively involved during the design of studies. Several alternative approaches for developing regions have been outlined (e.g., Altieri 2002; Anderson et al. 2001; Giller 2001).

Karlen et al. (2007) outlined and discussed different institutional arrangements (management models) for sharing resources and responsibilities between farmers and researchers. On-farm research often appears risky and costly to participating growers – especially when experimental treatments conflict with growers’ production objectives. Grower intervention in such situations can lead to lack of adequate experimental control (Karlen et al. 2007). From the researcher’s perspective, results of such on-farm studies may be site- or farm-specific with confounding sources of variation (Shennan 2008). However, on-farm studies also tend to be more realistic in terms of scale (field vs. plot), management practices used, and actual production constraints, while they also allow development of chronosequences (e.g., comparing system dynamic at different system development stages) within a relatively short period of time (Drinkwater 2002).

A workshop elucidating opinions of key stakeholders involved in the transfer and adoption of cover-crop-based systems in Latin America indicated that the key factor controlling adaptation of cover crops were nontechnical and include poor seed availability of annual cover crops (Anderson et al. 2001). In Northern Honduras, adaptation of *Mucuna* spp. as a cover crop in maize systems was abandoned by farmers if land tenure was not secure (Neill and Lee 2001). Additional hindrances for improved integration of cover crops in existing cropping systems may include local perceptions and policies (e.g., local research and extension staff favoring conventional high-input-based technologies to risk-averse small producer rather than fostering traditional legume-based mixed cropping systems (Anderson et al. 2001)). In many cases, researchers and policy-makers may promote their own political agenda (e.g., reducing environmental impacts, minimizing external inputs, and enhancing sustainability) instead of addressing end-user needs. Weil and Kremen (2007) reported that in Maryland, cover crops were only grown on 20–25% of the agricultural land during winter fallow despite farmers receiving $50–100 subsidies for growing such crops. Despite their inherent desire to provide good stewardship of local land resources, farmers face the reality of economic survival and may not be in a position to provide environmental services without tangible, direct benefits (Weil and Kremen 2007). Unless farmers are aware of these direct benefits of the use of cover crops, they may be reluctant to integrate them into their existing cropping systems. In many cases, the use of cover crops may not be cost-effective unless they provide multiple benefits and services (Avila et al. 2006a, b; Cherr et al. 2006b; Abdul-Baki et al. 2004).

3.2.1.3 Information and Technology Constraints

Constraints on cover crop use in Latin America include the lack of communication among different stakeholders (Anderson et al. 2001). In the Mid-Western USA, farmers indicated the greatest obstacle to development and adoption of cover-crop technology was lack of basic information (Singer and Nusser 2007). Armed with basic information about selection, management, and services of potential cover crops, many farmers might independently test and evaluate these species. Interestingly, much research has been conducted in these areas in North America. A search of the ISI Web of Knowledge for journal publications including “cover crop” or “green manure” or “living mulch” within the topic found over 10,000 manuscripts between 1923 and 2007. Over 61% of these manuscripts were recent (published since 1990) and most seem to be focused on North American production systems. Despite such an impressive increase in publication numbers, North American producers still cite lack of information about green manure and cover crops as one of the greatest barriers to their use (Singer and Nusser 2007). This indicates that information is not lacking, but that it is not transferred effectively.

Historically, most international agricultural research was commodity-based with the main focus being on increasing yields via intensification; use of interdisciplinary and participatory research approaches was limited (Altieri 2002). Over time, research has become more “integrated” and “holistic.” This may be related to increased integration of ecological approaches into mainstream agricultural research (Delate 2002) and the disillusion of green-revolution-based technologies to enhance the livelihoods of farmers in more marginal production settings (Bunch 2000). Current advances in system ecology may be thus used to design and test cropping systems with enhanced plant diversity to improve the functioning of agroecosystems rather than reinstating traditional crop rotations (Drinkwater and

Snapp 2007). However, considering the North American example, this evolution in research will almost certainly not lift constraints to cover-crop use unless producer's involvement is improved as well.

3.2.2 System Analysis

Effective research on cover crops inherently requires a system focus and use of long-term studies (Shennan 2008; Cherr et al 2006a). In the current academic climate, implementing this on a field scale may be challenging; extramural funding opportunities for applied long-term farming systems research are limited and within research institutions there exists a growing demand for scientists to generate information and publications quickly and focus more on fundamental research. As a result, most cover-crop publications focus on single system aspects including end-of-season biomass or N accumulation for specific production settings and final yields of subsequent crops. There are some research examples where the relationship between cover-crop growth and environmental conditions were captured (Cherr et al 2006b, Schomberg et al. 2007). When environmental conditions are known or can be predicted, models may be used for assessing cover-crop growth and subsequent decomposition, N release, and long-term impacts to other production systems. Likewise, such models can be applied for system analysis and design, by using field studies for development and calibration of these models (Stoorvogel et al. 2004). Within this context, the use of validated simulation tools will allow of extrapolation of results to other production settings or future scenarios. By utilizing on-farm data to develop and extrapolate such models, researchers therefore can more effectively identify benefits and constraints of cover-crop-based systems.

Integration of cover crops requires modification of the existing crop rotation schemes and design of the suitable alternative rotations (Selaya Garvizu 2000). Although this may be accomplished by trial and error, this is time-consuming, costly, and risky (van der Burgt et al. 2006; Keatinge et al. 1998). The need for quantitative assessment of complex systems across different production environments thus justifies the use of simulation models to integrate processes at a field scale in a more cost-effective manner (Sommer et al. 2007; Stoorvogel et al. 2004; Lu et al. 2000). The use of such models may provide a better insight into both short-term dynamics and long-term system behavior. This can facilitate an improved understanding of processes that are either difficult or costly to measure at different spatial and temporal scales such as long-term effects of cover crop residue management on erosion, production, profits, N leaching, and soil quality (Sommer et al. 2007; Dabney et al. 2001; Lu et al. 2000; Selaya Garvizu 2000).

Lu et al. (2000) used the EPIC model to compare the use of conventional, cover-crop-based, and manure-based corn–soybean systems for a period of 60 years. The authors showed that the use of cover crops could greatly reduce external fertilizer requirements and environmental risk, while gross margins were reduced only by 10%. These approaches may also be used to rapidly design viable alternative crop rotation schemes (Bachinger and Zander 2007; Dogliotti et al. 2003) or alternative production systems (Tittonell 2008; Dogliotti et al. 2005). Such models may range from simple integration of user knowledge and expertise to complex mechanistic models (Stoorvogel et al. 2004). Alternatively, models may focus on either tactical topics (e.g., with a focus on in-season management decisions) or strategic topics (e.g., design of long-term crop rotation or design and evaluation of alternative farming systems).

In terms of cover-crops systems, short-term decomposition dynamics of soil-applied cover-crop residues are typically included in models such as CERES-N, DAISY, NDICEA, and STICS (van der Burgt et al. 2006; Scopel et al. 2004; Berkenkamp, et al. 2002; Gabrielle et al. 2002; Quemada et al. 1997). However, surface-applied residues, which are a key aspect of no-tillage systems, tend to decompose slower owing to poor contact with soil microbes, prevalence of fungal decomposers, and drier conditions, while surface-applied residues also feature greater and more prolonged N immobilization (Schomberg et al. 1994). Thus, most crop growth models may not (accurately) model decomposition of surface-applied residues, which hampers their use to assess long-term effects of residue management or no tillage systems on soil quality and soil erosion (Sommer et al. 2007; Scopel et al. 2004; Schomberg and Cabrera 2001; Steiner et al. 1996). This limitation was overcome by developing surface decomposition modules or modifying decomposition parameters (Scopel et al. 2004; Quemada et al. 1997).

Since the Brundtland report, sustainable development has become integral part of the global policy agenda (Speelman et al. 2007). Within this context, when designing and managing cover-crops systems, operational tools are needed to evaluate their benefits in terms of enhancing sustainability of local natural resource management (NRM) systems within a larger socioenvironmental context (Lopez-Ridaura et al. 2002). This requires a conceptual framework that is participatory, comprehensive, meaningful, and practical, and MESMIS was developed to provide such a tool. This approach uses a cyclic process to aggregate and integrate economic, environmental, and social indicators, and it has been extensively used throughout Latin America (Speelman et al. 2007). The NRM systems are characterized in terms of key attributes (e.g., productivity), critical points are identified (e.g., poor adaptation of cover crops), and corresponding diagnostic criteria (e.g., ability to adapt new technology) developed, which are then translated into specific indicators (e.g., area in which cover crops are being used) that are readily available on a farm scale. The resulting information is then integrated by combining both qualitative and quantitative techniques with a multicriteria analysis (Lopez-Ridaura et al. 2002). Although the MESMIS has greatly facilitated participatory sustainability assessment, it does not allow for long-term system assessment, while the involvement of end-users was also often limited. Further modifications may thus be required so that it can be more effectively used for the exploration of alternative management systems and system optimization as well (Speelman et al. 2007). Moreover, use of simulation models may also facilitate trade-off analysis of different production components such as labor costs, profits, soil erosion, and environmental risk (Dogliotti et al. 2005; Stoorvogel et al. 2004; Lu et al. 2000).

3.2.3 Exploration of Alternative Systems

Model selection/development and application should fit into a larger system analysis framework as shown in Figs. 3.1 and 3.2. However, most existing models aim to enhance scientific understanding, whereas the use of such models for informed decision-making and improved management of cover crops requires a combination of sound scientific basis with practice-oriented model design (van der Burgt et al. 2006). Ideally, model development and application should be inspired by insights provided by farmers (e.g., participatory modeling). Examples of how models may be used in this fashion for the exploration, and design of more sustainable cover-crops-based vegetable production systems in Uruguay will be discussed in more detail later.

The use of the NDICEA model for exploration of more sustainable production practices for vegetable cropping systems in southern Uruguay demonstrated that cover crops could be effective in maintaining and/or enhancing SOM content while reducing external N-fertilizer requirements. However, these benefits differed between soil types (Selaya Garvizu 2000). This work was extended and model-based explorative land use studies were implemented to evaluate a much larger number of potential production systems, thereby providing a strategic support base for re-orientation of local vegetable production systems (Dogliotti et al. 2004). First, the ROTAT system (Dogliotti et al. 2003), a tool that was previously developed for generating crop rotation based on user-selected agronomic criteria, was used to assess all possible crop rotations. One proposed technical intervention was the introduction of cover crops and integrate pastures into vegetable cropping systems to reduce soil erosion and increase SOM. Key input and output parameters, including soil erosion, SOM and nutrient balances, environmental impacts, labor use, and economic performance were assessed by different quantitative standard methods using a target-oriented approach. This work generated a large number of

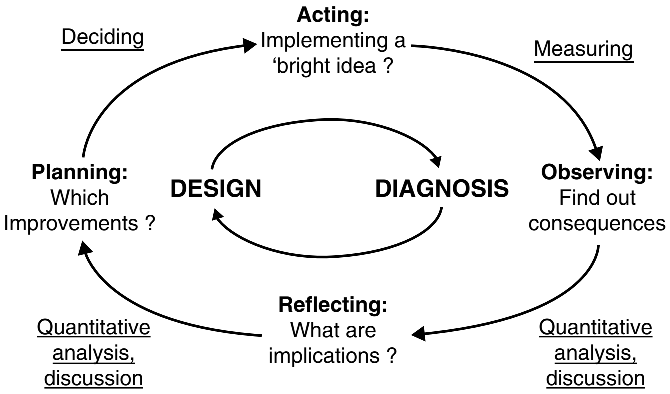

Fig. 3.2 Key aspects (diagnosis vs. design), system development steps (observing, reflecting, planning, and acting), and system develop actions (measuring, analysis/discussion, and deciding/selecting) during experiential learning cycle (Rossing et al. 2007)

alternative production systems, and across these systems, the use of cover crops reduces soil erosion on the average by 45–50% (Dogliotti et al. 2004). By using a mixed linear programming model (Farm Images), production activities could be allocated to production fields differing in soil quality in such a manner that production constraints were met, socioeconomic benefits were maximized, while soil degradation and environmental impacts were minimized. The model was then used to redesign seven local farms, and results showed that erosion may be reduced by 200–400%, the decline in SOM may be reversed, and when compared with the current situation, farm income could be improved for six out of seven farms (Dogliotti et al. 2005). Based on this work, it was concluded that using cover crops during the intercrop period and decreasing the area under vegetable production provide a more sustainable and profitable development option when compared with the current farmer's practice of increased intensification (Dogliotti et al. 2005). This work was then extended to a large number of farm types (based on farm size, soil quality, and supply of labor, irrigation, mechanization using a similar approach to assess the impact of resource endowment on development options and strategic farm design). An example of this approach for assessing the benefits of cover crops on reducing soil erosion and improving SOM content is shown in Fig. 3.3. Finally, it was also shown that farm resource endowment may limit sustainable development options, while reducing environmental impacts is quite likely to reduce family income as well (Dogliotti et al. 2006).

In terms of active farm participation, the FARMSCAPE approach (Carberry et al. 2002) outlines strategies for integrating participatory action research with simulation model approaches. One key finding was that it is critical to first establish the credibility of such models by linking them with on-farm studies and farmers' experiences. Moreover, active participation of pilot farmers was required and simulation tools needed to be flexible so that they can be adapted to specific on-farm management conditions. Via interactive dialogues between farmers and researchers, farmers were able to explore their production system and design alternative management practices similar to the "learning from experience," while this approach can greatly reduce the cost and risk associated with "trying new things" (van der Burgt et al. 2006; Carberry et al. 2002). However, assessing overall ecosystem functioning and services using simulation models remains difficult because of the inherent complexity of biophysical and human dimensions of these systems combined with the ecological and economic processes that control them, and the lack of site-specific data (Sommer et al. 2007). Alternative and more pragmatic approaches may thus be required as well, including the development of sustainability indicators such as MESMIS as discussed earlier.

Another instance of a design tool for cover-crop-based systems includes GreenCover (Cherr et al. unpublished; http://lyra.ifas.ufl.edu/GreenCover). This expert system is based on a systematic approach and aims to render information about cover-crops-based systems more relevant, accessible, and organized for potential users by (1) distilling basic "rules" about successful use of cover crops from published studies; (2) applying these rules to farm-specific environment, management, and goals; and (3) using the application of the rules to identify potentially

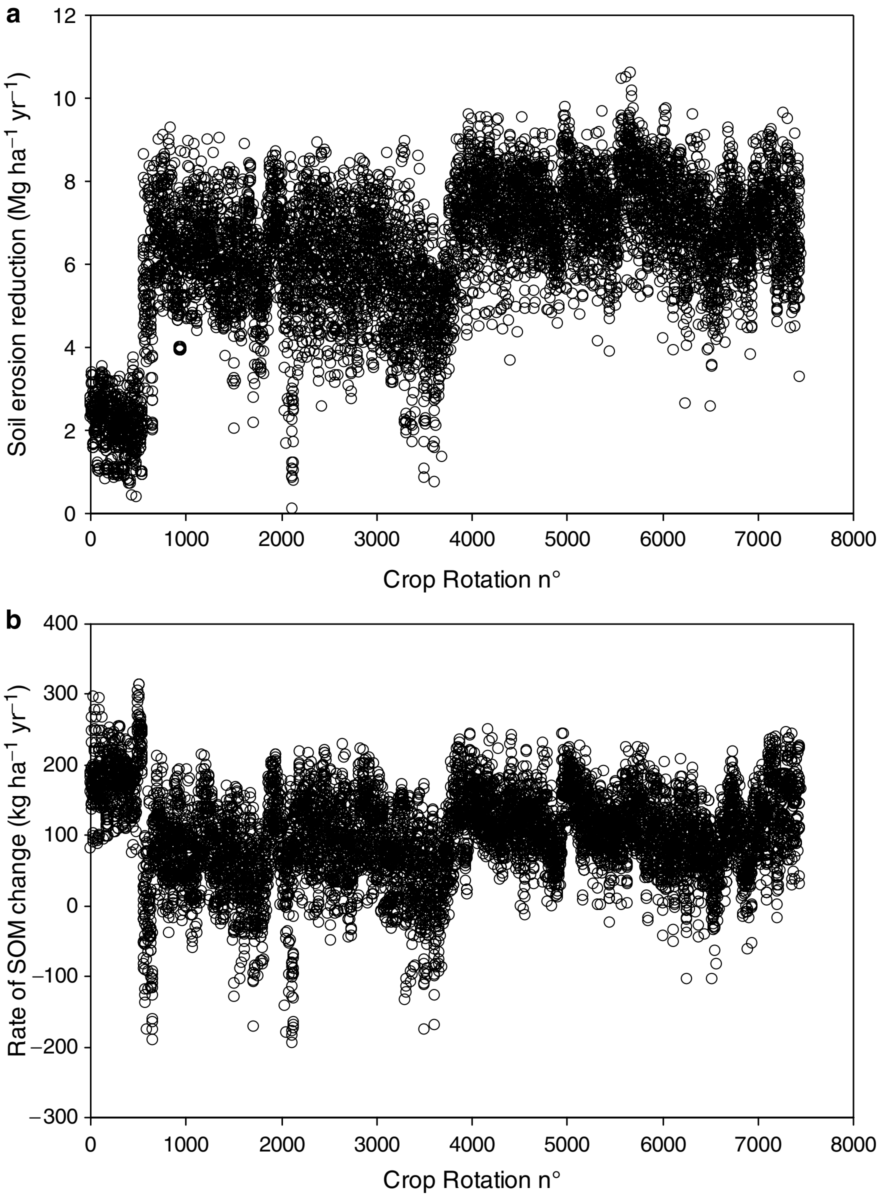

Fig. 3.3 Example of use of simulation models to explore potential benefits of including cover crops during the fallow period on reducing annual soil erosion (**a**) and improving soil organic matter content (**b**) for 7447 different crop rotation schemes in southern Uruguay. Overall soil erosion values were 13.2 versus 6.9 Mg ha^{-1} year^{-1} for conventional versus cover-crop-based systems, whereas corresponding values for soil organic matter (SOM) changes where −223 versus 100 kg SOM ha^{-1} year^{-1} (Modified from Dogliotti et al. 2006)

suitable cover-crop species from a database containing characteristics of roughly 50 species or species mixtures. In this tool, the user is provided with a list of the species and/or species mixtures as well as links to online management information sources. This kind of approach can be termed as an "information-access tool." It allows users to interactively explore how changes in management or targeted cover-crop services affect the selection process of cover crops.

3.2.4 Design or Selection of a System

Here, we emphasize modes of cover-crop technology development, adaptation, and transfer as examples of system design or selection. A more detailed discussion on cover-crop management is presented elsewhere (Scholberg et al. 2009). As mentioned earlier, this can also provide insights into the other components of the innovation framework already described.

3.2.4.1 Technology Development and Adaptation

The process of technical innovation of agroecosystems includes elements of continuous generation of "novelties" (Roep and Wiskerke 2004). These may include different constellations of evolutionary variations of native management techniques, local adaptation/simplification of imported high technology, and more revolutionary or external innovations (Douthwaite et al. 2002; Bunch 2000). Innovations can be simple, e.g., new cover-crops species, or complex, e.g., complete technology package including alternative rotations, new varieties, and equipment.

It is critical to first test a "promising technology," which may be imported from a different production environment on a limited field scale under controlled conditions (e.g., on-station initial screening and development). This may be followed by on-farm testing and further adaptation of the technology in close collaboration with local stakeholders prior to wide-scale promotion of such a technology (Giller 2001). As an example, zero tillage may be perceived as a revolutionary technology that aims to enhance soil ecological functioning and minimize soil degradation of arable cropping systems (Triplett and Dick 2008). Initial adoption of zero tillage after its development in the 1950s was slow and only after a suitable "basket of technology" was developed, e.g., development of special planters, suitable herbicide programs, and accumulation of local expertise. Transfer of cover-crop-based zero tillage systems to other systems that also aimed to minimize the use of herbicides (e.g., organic systems) required development of special roller equipment as well (Creamer and Dabney 2002; Kornecki et al. 2004).

During the adaption process (innovation cycle), close interactions occur between developers (innovative farmers/engineers/researchers), novelties (technical innovations), facilitators (extension workers or pilot farmers), and end-users (farmers). During this initial innovation cycle, developers elucidate farmers' expert knowledge to design a suitable set of technological innovations ("best bet" technology), which is then adopted and implemented by pilot farmers on a field scale ("plausible promise"), as discussed by Douthwaite et al. (2002). This may imply further refinement of technological innovations due to prevailing pedo-climatic conditions, farmer's knowledge and management practices, and socioeconomic factors (Nyende and Delve 2004). During the overall innovation process, there is a gradual transfer of participation and ownership of the innovation from the developer to the adopter who in time becomes the main driving force behind technology transfer (Douthwaite et al. 2002; Neill and Lee 2001).

The key to successful integration of cover crops in zero-tillage systems was the development of appropriate equipment for seeding crops (Triplett and Dick 2008). Such planters needed to be heavier and may also contain row cleaners to push aside crop residues and spoked closing wheels to ensure optimal soil structure and seed–soil contact along with the use of stronger and adjustable pressure springs to ensure a constant seeding depth (Sustainable Agricultural Network 2007). However, this "best bet" technology needed to be further adapted to include strip till ("plausible promise") for vegetable crops to prevent delays in crop development and thus ensure that growers can benefit from favorable market windows (Phatak et al. 2002). As an example of scaling out, the use of cover crops is often closely linked to zero tillage (Landers 2001), which was developed in the USA during the 1950s and introduced in Brazil during the 1970s (Triplett and Dick 2008). However, it only became more widely adopted in the 1980s. Currently, it is not only commonly used in the USA but also spread to Brazil, Argentina, and Australia (Triplett and Dick 2008). Another example of effective scaling-out of cover crops includes the widespread success and adaptation of mucuna-based maize production systems in Honduras. This process was driven by a spontaneous farmer-to-farmer diffusion-based dissemination. This mechanism for technology transfer was shown to be much more effective than the traditional extension model of technical assistance in different regions (Landers 2001; Neill and Lee 2001).

3.2.4.2 Approaches for Technology Transfer

In practice, promising technical interventions for enhancing the livelihood of farmers and the sustainability of agriculture are often not effectively adopted by farmers (Nyende and Delve 2004; Tarawali et al. 2002). As a result, especially resource-poor farmers often did not benefit from most technological innovations in the past, since they were typically neither appropriate nor affordable (Bunch 2000). Furthermore, traditional approaches for research and technology transfer tend to be reductionist (Drinkwater 2002), lack a "total system" approach (Phatak et al. 2002), and thus are poorly suited for cover-crop-based systems (Cherr et al. 2006b). Moreover, such systems should be designed based on specific biophysical conditions, while technological innovations should also be appropriate within the local socio-economic context (Cherr et al. 2006b; Douthwaite et al. 2003). Thus, limited adoption of technical innovations may be related to (i) lack of farm-tested appropriate and cost-effective technology; (ii) timing conflicts with the existing operations; (iii) lack of tangible/direct benefits and/or multiple services; (iv) limited access to resources (including capital and seeds); (v) poor matching of interventions with farmers' priorities; (vi) lack of active participation of farmers during technology development, adaptation, and transfer; (vii) lack of suitable policies and legislation to provide a broader societal support network (Morse and McNamara 2003; Nyende and Delve 2004; Tarawali et al. 2002; Landers 2001). These adaptation factors may vary greatly among regions; for example, the integration of cover crops in some systems (e.g., Brazil) has been successful on a regional scale (Calegari 2003; Landers 2001), while their adaptation in other regions (e.g., SE USA) lagged behind (Phatak et al. 2002). Moreover, technologies should be linked to local traditional knowledge, practices, and experience. Technological innovations thus need to be appropriate within the local context while direct involvement of farmer's at all critical development and adoption stages appears to be critical (Leeuwis 1999). Furthermore, active participation of early adopters during the refinement and dissemination of cover crops systems tends to greatly enhance technology transfer efficiency (Tarawali et al. 2002).

A large number of alternative approaches to conventional research and extension approaches have been proposed and are being used including (i) farming systems research and extension (Weil and Kremen 2007), (ii) farmer participatory research (Giller 2001, Bentley 1994), (iii) campesino-to-campesino approach (Anderson et al. 2001), (iv) prototyping (Vereijken 1997), (v) prototyping combined with model-oriented approach (Bouma et al. 1998), and (vi) co-innovation (Rossing et al. 2007). The first approach aimed to use a more "holistic" and interdisciplinary team approach to facilitate improved understanding of local farming systems and constraints, thereby facilitating the design of more appropriate development options (Douthwaite et al. 2003). However, this method is often rather descriptive and also does not effectively use technological tools including simulation models (Stoorvogel et al. 2004). The second method recognizes that farmers have valuable experience-based knowledge that complements science-based research approaches and that farmers can also be instrumental in structuring both research objectives and suitable technical innovations (Cardoso et al. 2001). Moreover, active involvement of farmers is critical, since any intentional change requires awareness while change in human conduct is also rooted in both individual and collective learning processes (Leeuwis 1999). Fostering active involvement will induce empowerment, which in turn further enhances technical innovation (Cardoso et al. 2001). Although this sounds appealing, its implementation may be challenging owing to social, cultural, and intellectual barriers between farmers and researchers. Moreover, for this method to be successful, a long-term commitment is required from both parties involved (Bentley 1994), which is exemplified by successful participatory projects (Altieri et al. 2008; Cardoso et al. 2001).

The "campesino-to-campesino" approach in Latin America dates back to the 1970s. It has its roots in the popular education movement, and it includes "reflection-action-reflection" elements and emphasizes local empowerment, which is implemented by transferring the control of the development process to the local community. Locally selected farmers (campesinos) also assume leadership, are actively involved in experimentation, coordinate the promotion and transfer of technical innovations, and at times may be paid part time for their contributions (Anderson et al. 2001). However, this approach requires an appropriate social environment as was the case in, e.g., Nicaragua. In other regions (e.g., Florida), commercial farmers may perceive their technological innovations as a tool to provide them with a competitive edge and may be reluctant to share intrinsic knowledge on such innovations.

Prototyping involves close interaction with farmers to define/rank objectives and to select the corresponding parameters that can be readily quantified (diagnosis and analysis phase). These parameters are then integrated using multiobjective methods to develop a conceptual design (prototype) of an alternative production system (design phase). Subsequently, this "prototype" is implemented, tested, and refined on a field scale in collaboration with selected pilot farmers (rediagnosis and/or redesign phase), before being disseminated to a larger group of farmers (Vereijken 1997). One limitation of this approach is that only a few production systems can be tested in the field (Dogliotti et al. 2004). Stoorvogel et al. (2004) combined the prototyping approach with a model-oriented system analysis approach. However, the active contribution of farmers appeared to be limited (e.g., top-down approach) and the basis for sustainability assessment rather narrow when compared with, e.g., MESMIS (Lopez-Ridaura et al. 2002).

The co-innovation approach is based on the premises that development is a "social" rather than a "technical" process (Douthwaite et al. 2003) and that technology development occurs through a continuous evolving experimental learning and selection process by farmers (Douthwaite et al. 2002). However, use of a system approach to foster systemic innovation rather than incremental change is also critical to revolutionize the technology transfer process. Moreover, the use of an interdisciplinary approach combined with effective use of simulation models may greatly facilitate the selection of suitable development options (Rossing et al. 2007). Full integration of all these components (co-innovation) thus seems to provide a powerful tool for fostering technology development, system design while also enhancing the efficiency of technology transfer and adaptation. Active participation of farmers during the problem identification phase (e.g., development of "problem trees," as shown in Fig. 3.4) and "fine-tuning" of technical interventions (e.g., during the exploration and design phase) aim to structure solutions that are appropriate within the local context (Anderson et al. 2001). Moreover, use of the "impact pathways" approach, which involves a frequent self-reflection and monitoring of the mutual learning process and development trajectory, allows both researchers and end-users to carefully monitor how development tracks and corresponding impacts evolve over time (Douthwaite et al. 2003).

An example of key aspects of the integration of a system analysis method used in the co-innovation approach will be illustrated based on an Uruguay case study. In this case, the decline in sustainability of local vegetable systems could not be reversed by simple adjustments of single production components or using standard technological innovation packages. Instead, a redesign of the farm systems as a whole was required. However, such a redesign of farm systems at the strategic level

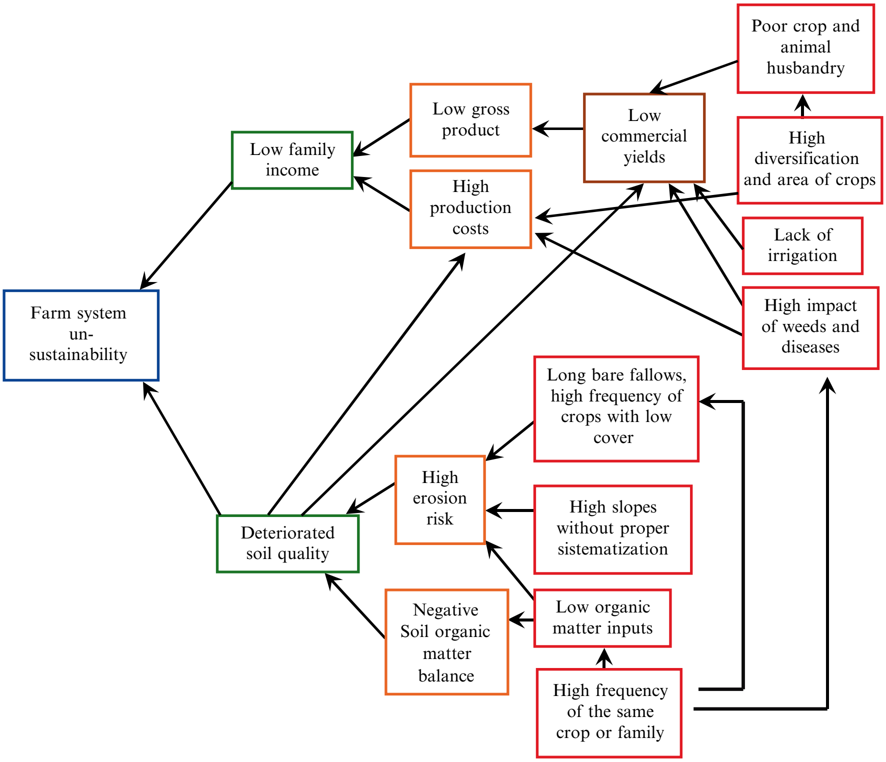

Fig. 3.4 Problem tree, which serves as an initial system diagnosis tool, as identified by a commercial vegetable producer in Uruguay. This diagram exemplifies potential benefits of cover crops to enhance crop diversity, suppress weeds, improve soil cover, and inherent soil fertility of erosion-prone intensive vegetable production systems

could only be achieved by a participatory, interdisciplinary systems approach. Field surveys showed that none of the farmers used cover crops as a standard practice during the intercrop periods and only 27% of the farmers had ever grown a cover crop. Most of the farmers used a tillage fallow during the 3–8 month period in between crops. Only 40% of the farmers intentionally tried not to grow the same crop in the same field next season, while 88% of the farmers did not follow an intentional succession of two specific crops (Dogliotti et al., 2003). Moreover, the maximum time horizon for planning the use of a particular field was less than 1 year for 80% of the farmers (Klerkx 2002). The added costs of growing cover crops accounted for just a fraction of total production cost of vegetables and this extra cost was also readily offset by reduced fertilizer cost and increased crop yields (Dogliotti et al. 2005). The lack of machinery for mowing and incorporating large amounts cover crops residues was perceived to be a constraint by some farmers. But the main limitation for adoption appeared to be the short time horizon of planning of farms' fields use and the lack of defined crop successions or rotations. This survey thus revealed that allocation of crops to fields is rather an "operational" or “tactical” decision than a “strategic” one, and despite the promising results of cover-crops-based systems in experimental stations and farmers’ fields, their use was not adopted by farmers in the region. The use of simulation-models and expert systems (e.g., ROTAT, Dogliotti et al. 2003) facilitated the exploration of cover-crop-based crop rotation systems that were appropriate within the local context. These initial explorations were then modified based on discussions with local producers, and their feedback was used to “fine-tune” system design prior to on-farm implementation of these systems.

3.2.4.3 Sustainability of Technology Adoption

In addition to inducing change and improvements, technological innovation should also aim to harness long-term sustainable development. Although farmers may be enticed to adopt innovations based on perceived short-term benefits, it may be more difficult to assess how such innovation meets the stability, resilience, and reliability criteria listed by Lopez-Ridaura et al. (2002). Assessing the medium to long-term effects of innovations on agroecosystem functioning is difficult and time-consuming (Drinkwater 2002) and may require use of simulation models (Stoorvogel et al. 2004). Increased management complexity and greater perceived risk may hamper adoption and long-term use of ecology-based systems (Shennan 2008), which can hamper both short-term adoption and long-term use of cover-crops-based systems. In Honduras, extensive adoption of mucuna-based corns systems was abandoned by many farmers within a few years due to changes in land-tenure, invasion of an obnoxious weed, and extreme weather conditions (Neill and Lee 2001). Although simulation models may not capture all potential contributing factors, they may facilitate improved risk assessment for different scenarios. This may be especially important in the context of current trends in climate change and more frequent occurrence of erratic and extreme weather and rainfall patterns (Stoorvogel et al. 2004). Finally, it was also argued that broadening the global genetic base of cover crops proposed for development options needs to be considered (in order to minimize the risk of build up of pests as was the case of *Leacaeana psyllid*). Therefore, diversification of the proposed innovations and developed options will be critical for long-term sustainability of cover-crop-based systems (Anderson et al. 2001). However, preservation and improved integration of traditional knowledge on cover crop practices will be critical as well to prevent an erosion of a collective heritage that took thousands of years to evolve (Altieri 2002).

3.3 Innovations in Cover-Crop-Based Systems in Case Study Regions

Below, we provide a brief historic perspective on key factors related to innovation in cover-crop-based systems in four regions of the Americas (Florida, USA; Paraná and Santa Catarina, Brazil; and Canelones, Uruguay). Special emphasis is placed on the components of the innovation framework discussed in the previous section: (1) characterization and diagnosis of constraints, (2) analysis of system behavior, (3) exploration of alternative systems, and (4) design of more sustainable production systems. In most cases, we also outline key factors affecting technology transfer and adoption within the context of local socioeconomic conditions and prevailing management practices.

3.3.1 Florida

3.3.1.1 Biophysical Production Environment

The study region (North Central Florida) is located in the Southeastern U.S. (29°25′ N and 82°10′ W). The average temperature is 19°C, and frosts may occur between November and March. Average annual rainfall is 1,200 mm with 52% of this rainfall occurring from June to September. With an area of 2.5 million ha and a total revenue of $7.8 billion, agriculture is a key component of Florida's economy (NASS 2007). The statewide average farm size is 99 ha and citrus (251,568 ha), sugarcane (163,968 ha), hay production (105,263 ha), vegetable crops (179,800 ha), peanuts (130,000 ha), and cotton (103,000) are some of the key agricultural crops. Their corresponding contributions to statewide farm revenues were 21.1, 5.5, 1.4, 24.0, 0.9, and 0.4%. In comparison, ornamental crop and livestock operations contributed 12.6% and 18.7% to statewide farm revenues, respectively (NASS 2007). The dominant soil types in the study region include excessively drained sandy soils (>95% sand) containing only 1–2% soil organic matter and soils typically have poor water and nutrient retention capacities (Cherr et al. 2006c; Zotarelli et al. 2007a, b). Most vegetable crops are produced using raised beds covered with plastic mulch in combination with drip irrigation (Zotarelli et al. 2008a, b).

3.3.1.2 Characterization and Diagnosis of Constraints

Within the US, Florida is the largest producer of citrus, tomatoes, sweet corn, watermelon, and snap bean and the second largest producer of bell peppers, cucumbers, and strawberries (NASS 2007). Current concerns about global warming and environmental quality issues will require growers to make more efficient use of water and nutrients and reduce inorganic fertilizer use (Cherr et al. 2006c; Zotarelli et al. 2008a, b). Historically, Florida has greatly depended on the use of fumigants to control weeds, pathogens, nematodes, and insects, and it is one of the largest users of methyl bromide. Future restrictions on the use of methyl bromide may undermine the viability of vegetable production in this region because the cost-effectiveness of alternatives to this fumigant remains an issue (Abdul-Baki et al. 2004). Increased globalization and lifting of trade barriers have also resulted in increased competition with other production regions (e.g., Brazil and Mexico), which have lower labor cost and less restrictive environmental regulations.

Steep increases in fertilizer, fuel, and labor costs along with citrus canker, and citrus greening disease epidemics are among the main concerns for citrus growers in the region. Since inherent soil fertility is poor and potential nutrient losses are appreciable, conventional growers mainly depend on chemical fertilizers (Zotarelli et al. 2008a, b). Organic growers often use external nutrient sources that are expensive, and their use may be restricted by food safety or certification issues (for example, animal manure). For organic growers, effective weed control is one of the key factors hampering successful transition, and cover crops may thus provide them with a cost-effective option to manage weeds (Linares et al. 2008). In our experience, the presence of coarse sandy soils hampered build up of SOM and effective inoculation of leguminous winter cover crops, and supplemental K-fertilizer was required to enhance cover crops performance. Warm-season cover crops, on the other hand, generally thrived on these sandy soils and are readily colonized by native rhizobium species (Linares et al. 2008).

3.3.1.3 System Analysis and Exploration of Alternative Systems

Use of Cover Crops for Weed Suppression in Orchard Systems

Organic vegetable growers in Florida tend to use a weed fallow during the hot and humid summer months, since high pest and disease pressures prevent the cultivation of most commercial crops. However, this practice may also favor build-up of weeds (Collins et al. 2007), while effective weed control remains a key concern of most organic growers (Ngouajio et al. 2003). Therefore, the use of summer cover crops such as sunn hemp (*Crotalaria juncea*) and cowpea (*Vigna unguiculata*) may provide growers with an option to improve inherent soil fertility, prevent the build-up of weed seedbank, and suppress noxious weeds such as yellow nutsedge (*Cyperus esculentus*) and Pigweed (*Amaranthus hybridus*). Greenhouse studies showed that sunn hemp provided relatively poor weed control during initial growth when compared with a more compact crop such as cowpea (Collins et al. 2007). However, field studies showed that sunn hemp was most effective in suppressing weeds toward the end of the growing season, which may be related to its slow initial growth (Linares et al. 2008). Thus, effective weed suppression in annual Florida organic systems may require use of cover crops with complementary growth and canopy characteristics.

Cover crops have been used extensively in perennial production systems throughout the world – especially tree-crop and shrub-crop production systems (Anderson et al. 2001). Some of the main issues of their use are related to effective weed control, uniform and compact growth, adequate erosion control, provision/retention of nutrients, and potential competition for water under water-limiting conditions. Effective use of cover crops may reduce establishment (e.g., fertilizer) cost and/or provide financial returns (e.g., forages and pulses) during the tree establishment period (Anderson et al. 2001). In terms of perennial production systems in the subtropical and tropical regions, the following warm-temperature adapted perennial and annual species may be viable candidates: perennial peanut (*Arachis pinto* and *A. glabrata*), *Canavalia* spp., pigeonpea (*Cajanus cajan*), *Crotalaria* spp., indigos (*Idigofera* spp.), velvetbean (*Mucuna* spp.), and *Vigna* spp. (Linares et al. 2008; Anderson et al. 2001). However, use of *A. pinto* is not feasible in North Florida due to winter freezes. In this region, winter annuals most commonly used in perennial systems include winter rye, vetch, black oats (*Avena strigosa*), crimson clover (*Trifolium incarnatum*), lupin, and forage radish (*Raphanus sativus*). We tested each of these species for weed control potential in an organic citrus production system in North Florida.

Of the warm-temperature cover-crop species we tested, sunn hemp (*Crotalaria juncea*) was the most prolific cover crop. It generated 5.3–12.6 Mg ha^{-1} when compared with 5.9–9.5 Mg ha^{-1} for hairy indigo, 3.7–7.6 Mg ha^{-1} for pigeon pea, 2.4–5.1 for Mg ha^{-1} for cowpea (*Vigna unguiculata*), and 1.0–2.8 Mg ha^{-1} for velvetbean (*Mucuna pruriens*). Both sunn hemp and cowpea were most effective in suppressing weeds and reduced weed biomass by 83–97% (Linares et al. 2008). Pigeon pea did not provide effective weed control; similar observations were made with citrus in Bolivia (Anderson et al. 2001) and Brazil (Matheis and Victoria Filho 2005). We used both "bushy" and "vining" Mucuna types, but neither performed well under our conditions; this may have been related to the poor water retention capacity of our sandy soils. This is in contrast with studies in Central America where velvetbean grew more vigorously and provided effective weed suppression (Neill and Lee 2001). Although we tested jackbean (*Canavalia ensiformis*) on a small plot basis and this crop appeared to be well adapted to sandy soils, lack of access to seed sources prevented detailed assessment of its performance. In other regions, this crop is a prolific biomass producer, grows well under adverse conditions, is used for forage production as well, and is also suitable for intercropping (Nyende and Delve 2004; Anderson et al. 2001).

In terms of winter cover crops, the best performing species were winter rye (3.2–6.0 Mg ha^{-1}), forage radish (3.2–4.3 Mg ha^{-1}), crimson clover (1.7–5.0 Mg ha^{-1}), and black oats (1.3–3.6 Mg ha^{-1}). Use of cover-crop mixtures (one or more species) greatly enhanced biomass production (3.6–8.0 Mg ha^{-1}). Crop performance and weed suppression by winter leguminous cover crops were erratic during the first years, which were related to the poor adoption to sandy soils, but over time, their performance improved. Rye and radish were more effective in suppressing weeds while mixes of these two cover crops reduced weed biomass to less then 2% of that in controls and thus may provide a very effective weed control (Linares et al. 2008).

The initial growth of perennial peanut (*A. glabrata*) in this system was very slow and its initial weed suppression ability was poor. Repeated mowing improved the performance of this species over time, and it may provide a valuable forage for additional farm income. However, its growth and weed suppression during the first 3 years of study was clearly inferior to the annual cover crops tested.

Annual Cover Crops as a Green Manure in Vegetable Crops

Historically, crops such as velvet bean were used as a green manure until about the 1930s. After this time, the availability of cheap inorganic fertilizers reduced their attractiveness as N sources (Buckles et al. 1998). Currently, cover crops in Florida vegetable cropping systems are usually incorporated via tillage. However, since tillage enhances soil mineralization, this may offset carbon sequestration and soil quality benefits (Phatak et al. 2002). Conventional production systems for crops such as tomato and pepper include the use of black mulch, which serves to facilitate fumigation, suppress weeds, reduce evaporation, leaching, increase soil temperatures and initial growth, and prevent soil contact of harvestable products (Carrera et al. 2007). However, its use involves energy, economic and environmental costs for production, and purchase and disposal, while their use also can enhance run-off of pesticides (Abdul-Baki et al. 1996, 1999). Experiments conducted by Abdul-Baki et al. (2004) in South Florida demonstrated that cover-crop-based systems (e.g., growing cowpea or velvet bean) had similar marketable tomato yields when compared with the use of mulch and methyl bromide, while production cost could be reduced by $1,544 ha^{-1}. On-farm demonstration trials by Avila (2006c) in South Florida showed that use of sunn hemp-based systems could offset marketing risk of conventional tomato systems by increasing yields and reducing use of herbicide and external fertilizer inputs. These findings were similar to those of previous studies in which systems based on cover crops and zero-tillage improved soil quality and nutrient retention while reducing agrochemicals, external input use, production costs, environmental impacts, and soil erosion (Abdul-Baki et al. 1996, 2002, 2004).

Another field study was conducted in north central Florida to assess the benefits of a reduced-tillage cover-crop-based system for vegetable crops between 2001 and 2005. This study included different combinations of both summer and winter cover crops [sunn hemp, rye (*Secale cereale*), lupin (*Lupinus angustifolus*), and vetch (*Vicia* spp.); Avila et al. 2006a, b; Cherr 2004). Overall biomass and N accumulation of summer cover crops were on the order of 8.0–12.2 Mg ha^{-1} and 146–172 kg N ha^{-1} whereas production of leguminous winter cover crops was much lower (2.0–4.0 Mg ha^{-1} and 51–104 kg N ha^{-1}) (Cherr et al. 2006c). However, in the warm and humid climate, most of the N from winter-killed sunn hemp was released quickly, and growth of subsequent cover crops and economic crops was too slow to effectively utilize it (Cherr 2004; Cherr et al. 2006a, c). The use of a vetch and rye biculture allowed uptake of this N and also resulted in improved winter-cover-crop growth and N accumulation (7.2 Mg ha^{-1} and 135 kg N ha^{-1}; Avila et al. 2006a, b). Changing rye and vetch proportions in this mixture greatly affected the C:N ratio of the cover-crop residue (e.g., 69 for pure rye system, 26 for 67% rye–33% vetch system, and 14 for pure vetch system). Although total biomass was greatest for mixed systems, N accumulation was greatest for pure vetch systems.

In terms of yield benefits to subsequent crops, cover-crops-based systems provided clear yield benefits for sweet corn, broccoli, and watermelon (Cherr et al. 2007; Avila et al. 2006a, b). However, unlike studies at more northern locations (Bhardwaj 2006; Carrera et al., 2007; Burkett et al., 1997), the cover-crops-based systems in Florida only provided limited yield benefits and inorganic N-fertilizer savings. Although the cover-crop-based systems provided N-benefits on the order of 60–70 kg N ha^{-1}, enhanced early economic crop growth, and N accumulation, these systems were still out-yielded by conventional controls receiving 267 kg N ha^{-1}

(Cherr et al. 2007). Generally, the low soil fertility combined with the poor nutrient retention capacity of Florida soils does not support top production levels unless substantial amounts of supplemental nutrients are supplied throughout the growing season. This is related to the prevailing sandy soils that hamper efficient nutrient retention and build-up of SOM even in the absence of tillage. Although cover-crop-based systems provide substantial amounts of both C and N, the enhancement of the inherent long-term nutrient supply capacity of the system appears to be limited, since SOM is poorly protected and nutrients released by residues are prone to leaching. Therefore, the system is poorly buffered, and thus pools are exhausted rapidly prior to the development of an extensive root system of the commercial crop. Pasture systems thus may be more effective in improving inherent soil fertility when compared with annual cover crops. Moreover, maize crops may be particularly unsuited to cover-crop-based systems in these conditions because its capacity for N uptake during early growth is limited. Detailed ^{15}N studies (Zotarelli unpublished data) showed that N-uptake efficiency of sweet maize was only 14% for soil nitrate present at planting when compared with 48% for N released 1 month after planting.

3.3.1.4 Technology Adoption

The adoption of cover-crop-based systems in Florida by farmers is limited and mainly confined to organic producers. Conventional growers may opt to use sorghum Sudan grass (*Sorghum bicolor* var. Sudan grass) during summer fallow and winter rye as a soil cover in commercial vegetable cropping systems. Although cover crops may be perceived as an environmentally sound management option, their use can interfere with the standard management practices in conventional systems in this region. In an on-farm study, it was observed that full-grown sunn hemp was very tall (>2 m), and the thick-stemmed plants produced a recalcitrant residue layer. During subsequent bed formation of tomatoes, this material hampered bed formation and thereby reduced the effectiveness of fumigation and subsequent weed suppression since the residue caused tearing of the plastic mulch. Based on suggestions of the participating grower, use of repeated mowing resulted in a less coarse residue material and acceptable biomass benefits, which underlines the importance of active farm participation during technology development.

In Florida, the absence of incentives, lack of appropriate recommendations, and suitable equipment may hamper widespread adoption of cover-crop-based systems in vegetable cropping systems. Since the use of zero- or reduced-tillage on sandy soils in Florida is limited and there is a lack of suitable planters, the risk of poor initial crop establishment and yield reductions of subsequent commercial crops also increases. These factors may further hamper the use of cover-crops-based conservation systems in the region. In contrast, 58–64% of the farmers in neighboring Alabama use reduced- or zero-tillage for crops such as cotton and maize (Bergtold et al., 2005). Even in North Florida, there may be producers within subregions or niche markets for whom cover-crop use is more feasible. On the heavier soils in the northwest Florida panhandle, there is more of a tradition to integrate reduced tillage into conventional operations while leguminous winter cover crop also tend to perform better on these soils. Moreover, proximity to Alabama and Georgia may provide opportunities for farmers in this subregion to successfully adapt cover crops systems developed in these neighboring states as well. Both positive and negative incentives (price premiums and regulatory requirements, respectively) may also encourage organic growers in Florida to use cover-crop-based systems. In this case, lack of technical information by traditional local extension approaches and different pedo-climatic conditions from other key organic production regions may force growers to engage themselves with on-farm experimentation and technology development of cover-crop-based systems. So, it appears that lack of incentives and suitable technologies continues to hamper the adoption of cover-crop-based in conventional production systems. While in organic systems, where cover crops can provide a much broader array of services, the lack of viable alternatives justifies development of cover-crop-based systems.

3.3.2 Brazil

3.3.2.1 Biophysical Production Environment

The study region (Paraná) is located in the Southern region of Brazil between latitudes 22°29′S and 26°42′S and longitudes 48°02′W and 54°37′W. Paraná is located in the tropical and subtropical transition zone. The climate is humid-subtropical with hot summers and drought periods no longer than three to four weeks. The mean annual precipitation ranges between 1,400 and 2,000 mm. Most rain occurs during the summer (October–March). Almost 40% of Paraná’s area consists of soils derived from basalt beds with heavy clay and fertile soils. In this region, agricultural cropping systems mainly include annual crops such as soybean, wheat, cassava, sugarcane, cotton, and coffee. In the northwest, soils derived from sandstones dominate, and in this region beef cattle and orange production are of greater importance. The agricultural acreage in Paraná amounts to 17.6 million hectare, of which 4.0 and 2.7 million hectare have been planted with soybean and maize, respectively. Nationally, Paraná is the largest producer of beans, maize, and wheat; and second in soybeans, cassava, and sugar cane; third in tobacco; and fourth in coffee. In 2007, Paraná grain production represented 22% of the national production (IBGE 2008). The grain production in 2006 was 11.9 million tons of soybean, 14.3 million tons of maize; 1.9 million tons of wheat; 0.7 million tons of beans. Key factors such as climate and soil have made it possible to produce a wide variety of crops. However, the success of agriculture in Paraná was possible due to efforts of the state research and extension agencies to implement long-term watershed-based soil and water conservation programs including a combination of zero tillage and cover-crop-based crop rotations.

3.3.2.2 Characterization and Diagnosis of Constraints

Intensive agriculture in Paraná started upon colonization during the early 1900s and the state was the main coffee producer for several decades. The area planted with coffee reached 1.8 million ha by 1975. At that time, however, a severe frost decimated coffee and most of the coffee fields were converted to mechanized annual cropping systems and pastures. Additional land was converted to arable land as well as more people moved into the area. Soybean–wheat-based crop rotations became the dominant cropping system during the 1970s and 1980s. These cropping systems featured burning of crop residues followed by tillage with heavy disc harrows and moldboard plows. Soil surface disaggregation, reduced soil water infiltration, soil crusting, and soil compaction led to severe erosion problems (10–40 Mg soil erosion ha^{-1} $year^{-1}$) and a steep decline in inherent soil fertility (Calegari 2003; Derpsch et al. 1986). Initially, terracing and planting along contour lines was promoted to minimize further erosion. However, during the early 1970s, zero tillage systems were also introduced in Paraná (Calegari 2003; Landers 2001). During the early 1990s, the acreage under zero tillage in Brazil reached 1 million hectare.

However, the adoption of zero tillage systems intensified other problems such as weeds and pests, and also exacerbated soil compaction, while it also posed problems associated with thatch layer accumulation. The development of soil management and cropping systems strategies, including the use of cover crops, thus became important research topics to improve the sustainability of local agriculture production systems in Paraná (Calegari 2003). In particular, research showed that diversification of crop rotations under zero tillage increased the average yield of soybean and maize and lowered fuel, fertilizer, pesticides, and labor requirements (Muzilli 2006; Calegari 2003). Additional benefits such as increase in soil carbon stock and cation exchange capacity, greater soil water infiltration and soil aggregation, and reduction of runoff have been frequently reported in the literature (Triplett and Dick 2008; Zotarelli et al. 2005a, b, 2007a; Sisti et al. 2004; Calegari 2003; Sa et al. 2001; Six et al. 2000; Boddey et al. 1997; Derpsch et al. 1986).

3.3.2.3 System Analysis and Exploration of Alternative Systems

Weed suppression by cover crops has provided a critical component in the successful adaptation of zero tillage systems in Paraná by cutting herbicide use and weed control costs by up to 25–42% (Teasdale et al. 2007; Derpsch 1998). Use of species, e.g., oats, rye, radish, lupin, and sunn hemp, that can be killed mechanically may further reduce or eliminate herbicide use but some manual weeding during the growth season may still be required (Teasdale et al. 2007). Selection of cover crops is based on local availability of affordable seeds, their effectiveness in providing soil cover and suppressing weeds, and to supply nutrients to a subsequent cash crop. Recommended cover crops in Paraná include oats (*Avena* spp.), white radish (*R. sativus*), pigeon pea, mucuna, vetches, lupins, lablab (*Lablab purpureus*), sunflower (*Helianthus annuus*), pearl millet (*Pennisetum glaucum*), and pastures (see also Calegari 2003).

Table 3.1 Examples of crop rotation systems recommended to Paraná (Embrapa 2006)

State region	Year 1	Year 2	Year 3	Year 4	Year 5	Percent of soybean
North/West	OA/MA	CA/SO	PM+M/SO	WH/SO	–	75
North/West/Central	LU/MA	OA/SO	WH/SO	–	–	66
Southeast	VE/MA	WH/SO	OA/MA	WH/SO	BA/SO	60–80

BA = barley; CA = canola; LU = lupin; M = mucuna; MA = maize; OA=oats; PM = pearl millet; SO = soybean; VE= vetch; WH = wheat

Soybean is the most important cash crop that is also grown most frequently (60–80% of rotations). Table 3.1 provides a brief description of standard recommended crop rotation for zero tillage systems in Paraná for different production regions. Crop rotation design is based on (1) species characteristics (legume vs. gramineae), (2) residue quality and quantity, and (3) occurrence of diseases and nematodes. In terms of fertility management, biological nitrogen fixation (BNF) plays an important role in the improvement of sustainability of local cropping systems. Soybean accumulates large quantities of N, 80% of which is generally supplied by BNF in rhizobium-inoculated varieties (Alves et al. 2006; Zotarelli 2000, 2005). However, owing to the high amount of N removed with the harvested product, relatively little of the N is left in the field (Alves et al. 2002). Under zero tillage conditions, the inclusion of winter legume cover crops such as lupin or vetch every 3–4 years in the crop rotation thus is critical to maintain SOM and inherent soil fertility and to minimize runoff and erosion via enhanced crop water infiltration and soil and nutrient retention. This has been shown to greatly enhance the yields and sustainability of local cropping systems (Derpsch et al. 1986). Well-managed zero tillage/cover-crop-based systems can reduce erosion by 95% (Prado Wildner et al. 2004). On-farm studies in North Paraná showed that zero tillage increased soybean and wheat yields by 34% and 14%, respectively; whereas corresponding additional yield benefits associated with integration of cover crops in crop rotations were 19% and 6% (Calegari et al. 1998).

Recent experiments in this region showed that lupin accumulated up to 10 Mg ha^{-1} of dry biomass with N accumulation around 250 kg ha^{-1}. The BNF contribution for lupin was approximately 70%, which translates to an input of approximately 175 kg ha^{-1} of external N being added. Lupin-based maize systems receiving no other N inputs yielded 47% more when compared with maize following oats receiving typical fertilizer rates of 80 kg N ha^{-1} (Zotarelli 2005). Integrating zero-tillage with winter cover crops also increased soil C accumulation (Sisti et al. 2004) via stabilization of aggregate-associated C (Denef et al. 2007; Zotarelli et al. 2007a). However, as soybean is the main cash crop, use of certain legume cover crops that host soybean diseases must be restricted [such as pigeon pea and lupin cover crops that also host stem canker (*Phomopsis phaseoli*)]. These problems may be solved by changing crop sequence within rotations and/or by using resistant soybean cultivars. Other challenges with cover crops include insufficient mulch layer formation or reduced emergence of subsequent economic crops when an adequate mulch layer is sufficient to provide other benefits. Again, these problems can be solved by relatively simple changes in management, such as lengthening the interval between the killing of the cover crop and maize planting and use of relatively recalcitrant cover crops (small grains or cover-crop mixtures including small grains).

3.3.2.4 Technology Adoption

One of the key contributing factors to the success of zero tillage systems was the diversification of crop rotations including the use of cover crops. More than 25 million hectare have been cultivated under zero tillage in Brazil in 2006 and, in the same year around 95% of grain crop land was under zero tillage in Paraná. Rapid expansion of cover crop and no till systems was greatly facilitated by participatory farming system approaches. These approaches gave farmers a central role during the problem identification, structuring of solutions and aimed also to strengthen linkages between researchers and extension workers (Sempeho et al. 2000). In general, farmer-to-farmer demonstration and dissemination approaches were the most effective. For larger farmers, both the private sector and experts from nongovernmental organizations (NGOs) also contributed to this process, whereas for smaller farmers, state extension agencies played a more important role (Landers 2001). However, the main boost in adoption occurred when production costs of zero tillage systems were less than those of conventional tillage, suitable recommendations were in place and the method was also effectively integrated in standard teaching and extension programs (Landers 2001). Other factors affecting adoption included: creating awareness of clear incentives for adoption of cover crop and zero tillage systems; active contribution of pilot farmers that championed zero tillage and adapted such systems to local conditions; presence of effective farm organizations; and access to subsidies or credit permitting farmers to invest in technology (Pieri et al. 2002; Sempeho et al. 2000). Moreover, local supply networks for affordable seeds, tools, equipment, and local knowledge were also critical to sustain the continuous development as they promoted local self-reliance ensured long-term sustainability of the effort (Pieri et al. 2002; Landers 2001).

3.3.2.5 Innovations in Cover-Crop-Based Conservation Tillage Systems in Santa Catarina

Santa Catarina is a hilly region in southern Brazil with heavy soils and high annual rainfall (1,200–2,370 mm), and 40–80% of the agricultural land is prone to medium to severe erosion (Prado Wildner et al., 2004). Similar to southern Uruguay, this region features relatively small-scale family-based intensive crop production systems. Some of the key crops include maize, beans, potato, and tobacco as well as intensively managed vegetable systems such as onion, garlic, tomato, cauliflower, pepper, and beets (Prado Wildner et al., 2004). Although there has been a trend of increased intensification and a rural exodus of farm workers, the hilly topography has hampered development of large-scale mechanized agriculture. During the 1960s, the use of terracing was promoted to stem soil erosion, but (as in Paraná) neither did this address the real problem (e.g., lack of soil cover) nor did it fit local needs, so adoption was poor. During the 1970s, increased mechanization resulted in extensive and devastating soil erosion.

Technical assistance to solve these problems was provided by neighboring institutes in Paraná state. Local extension agents initiated cover-crops-based zero tillage systems on pilot farms in 1978. To ensure availability of cover crops, farmers were provided with small quantities of common vetch (*Vicia sativa*), but they were required to multiply this seed locally. Availability of suitable seeds in Santa Catarina greatly varies depending on the species, year, and region. Relatively, few farmers specialize in the production of cover crops seeds, and in some years, seeds of leguminous cover crops may still not be available; therefore, this remains one of the main constraining factors for adoption of cover-crop-based systems. Despite this constraint, farmland in cover-crop-based zero tillage systems in the region increased from 5% in 1987 to 44% in 1997. This rapid expansion was related to a number of factors: (1) farmer-driven technology, (2) development of a variety of equipment by local entrepreneurs tailored to the specific needs of different farm management types and distribution of this equipment by larger agro-industrial companies, (3) reduced labor requirements from mechanization, which enhanced the livelihood of local farmers, (4) presence of an effective local agricultural research and extension network, (5) government abandoning subsidies for use of agroechemicals during the 1980s, (6) strong presence of family-based farming systems with secure land tenure, and (7) presence of NGOs that helped structure local education and research programs (Prado Wildner et al., 2004). Reported yield of local cover-crop-based maize systems were 30% higher when compared with the conventional systems. The use of cover crops combined with reduced tillage in this region was capable of increasing both SOM and fertilizer-use efficiency and lowering operational costs, but has increased herbicide requirements (Amado et al. 2006; Prado Wildner et al., 2004).

Onion production expanded greatly during the 1970s and 1980s in the Upper Itajai River Valley of the Santa Catarina region. The use of mechanical tillage on steep slope combined with fine textured soils in onion cropping systems that have sparse canopies and add very little residues resulted in pronounced soil erosion (Prado Wildner et al., 2004). Reduced-tillage systems were introduced to combat this problem and were adopted by 60–70% of the farms. Black oat, oilseed radish, and/or vetch are used as cover crops and these are rotated with onions, although onions still must receive supplemental N applications to minimize the risk of N-immobilization. Maize is frequently grown following onion and benefits from residual soil nutrients. In some cases, maize may be intercropped with mucuna, while *Canavalia* and *Crotalaria* species also can be effectively grown as summer cover crops, but farmers usually prefer intercropping with edible beans during this time. Over the years, these systems evolved and were also adapted by local organic farmers. However, in these systems, farmers opted to use a mix of different cover crops (e.g., a rye, radish, vetch mixtures) to enhance the functionality and performance of the cover-crops system (Altieri et al. 2008). The use of cover crops allowed the development of innovative organic reduced-tillage systems and reduced weed growth by more than 90% and thus provided farmers with a cost-effective weed management option (Altieri et al. 2008). On-farm studies in this region have used systems developed by local farmers based on native knowledge and innovations. The main role of researchers has been to provide suggestions and to make benefits of locally developed systems more explicit to a broader (international) audience. The success story of cover-crop-based systems in Brazil is closely linked to their integrative use in conservation tillage systems. Such initiative may serve as a development framework for other regions and systems with similar conditions, including both conventional and organically managed vegetable production systems in Uruguay.

3.3.3 Uruguay

3.3.3.1 Biophysical Environment

The study region (Canelones) is a hilly region located in Southern Uruguay (34°25′ S and 56°15′ E). The average annual temperature is 16°C (10°C in July to 23°C in January), and light frosts may occur between June and September. Average annual rainfall is 1,100 mm and water deficits tend to occur between October and March, while water surplus may be observed between May and August. Clay and silty clay loam soils prevail and SOM content for native undisturbed soils may range between 4.5% and 6.5% but may decline to 1–3% under continuous cultivation of conventional agricultural systems. Soil erosion due to intense rainfall events may result in soil losses of 9–15 Mg ha^{-1} year^{-1}. Soil degradation has resulted in soil crusting, reduced aeration, infiltration, and water retention capacity. More than 70% of the farms are smaller than 20 ha and vegetable production is the main source of income for 27% of growers. The main vegetable crops grown in the area include squash, carrot, onion, garlic, potato, sweet potato and sweet maize, and tomato.

3.3.3.2 Characterization and Diagnosis of Constraints

The Uruguayan vegetable production sector has been facing a cycle of increased production intensity and input prices, falling commodity prices, and depletion of natural resources. Between 1990 and 1998, vegetable production increased by 24%, crop yields increased by 29% while cropped area decreased by 9% (DIEA-PREDEG 1999). Simultaneously, inflation corrected prices of vegetable products between 1992 and 2001 decreased by 34% (CAMM 2002) and an additional 15% between 2001 and 2004 (CAMM 2005). Southern Uruguay has the highest concentration of small or family farms (farms where most of the labor is provided by family members).

Around 88% of the farms with vegetable production as main source of income are family farms (Tommasino and Bruno 2005). Between 1990 and 2000, the number of these vegetable farms decreased by 20% (DIEA 2001). Those farms remaining in business had to increase production and product quality, while reducing product prices to maintain family income.

The strategy followed by most farmers was to intensify and specialize their production systems. The average vegetable cropped area per farm in southern Uruguay increased, while the average total area per vegetable farm stayed approximately the same. The average number of crops per farm also decreased. The observed increase in crop yields was attained via increased use of irrigation, external inputs (fertilizers, biocides, and energy), and higher quality seeds (Aldabe 2005). However, this strategy intensified the pressure on the already deteriorated soils and limited farm resources. Only 27% of the farmers may at times use cover crops, while 90% of the farmers depend exclusively on chemical fertilizers (Klerkx 2002). Increasing crop area and narrowing crop types without an adequate planning has often interfered with farm operations and caused inefficient use of production resources, increased dependence on external inputs, and greater environmental impacts. Consequently, farm incomes are inadequate to cover basic family needs, to maintain farm infrastructure and preserve the natural resource base.

When farmers in Canelón Grande were asked what they perceived to be the main environmental problems, the most common responses were global climate (39%), pollution by residues of agrochemical products (15%), and problems with pests and diseases (11%). Only 9% indicated soil erosion as their main environmental problem (Klerkx 2002). However, 88% of the interviewed farmers were aware of the occurrence of soil erosion on their own farms. The use of terracing and maintaining a rough soil surface were practices that farmers typically perceived to be effective in controlling erosion, while only 8% mentioned the use of cover crops or the importance of maintaining adequate vegetation cover (Klerkx 2002). Lack of farmer knowledge about the benefits of cover crops, therefore, appeared to be a significant constraint to their use, thus hampering development and adoption of cover-crop-based systems in this region.

3.3.3.3 System Analysis and Exploration of Alternative Systems

During the 1990s, several experiments were conducted on experimental stations and commercial farms in South Uruguay to investigate the effects of cover crops and organic amendments on vegetable crop yields and soil quality. When compared with conventional management, these experiments showed significant increases in vegetable crop yields after cover crops and animal manure applications. In crops such as potato, sweet potato, onion, carrot, garlic, and sweet pepper, yield increases ranged from 9% to 65% after summer or winter green manures when compared with fallow (Docampo and Garcia, 1999; Garcia and Reyes, 1999; Gilsanz et al. 2004). Winter cover crops tested included oats, black oats, wheat (*Triticum aestivum*), and peas (*Vicia* spp.) in pure stands or in mixtures; summer cover crops were maize, sorghum (*Sorghum bicolor*), foxtail millet (*Setaria italica*), mucuna, cowpea, and *Crotolaria* species. Aboveground biomass production ranged from 3.5 to 11 Mg

DM ha^{-1} and 3 to 19 Mg DM ha^{-1} for winter and summer cover crops, respectively (Peñalva and Calegari 2000; Docampo and Garcia, 1999; Garcia and Reyes, 1999; Gilsanz et al. 2004).

Dogliotti et al. (2005) showed that erosion control support practices such as terracing are not adequate to decrease soil erosion below the tolerance limits in vegetable farms in South Uruguay. However, inclusion of cover crops during the intercrop periods and alternation of horticultural crops with pastures do have the potential to reduce soil erosion by a factor of 2–4 while reversing SOM losses, since SOM values increased with 130–280 kg ha^{-1} year^{-1} (Dogliotti et al. 2005). In 2005, a project was initiated by a local team of scientists to develop sustainable vegetable farming systems in six farms in the region. The study was extended to 16 conventional and organic farms in 2007. On each farm, the development process involved a continuous cycle of diagnostic-design-implementation-evaluation components, and initial results were used during a subsequent design and testing cycle as well.

In mixed farming systems, the use of perennial rye grass and red clover (*Lolium perenne* and *Trifolium pratense*) mixtures or alfalfa (*Medicago sativa*) can be a viable production option since it can provide a source of high-quality forage while also enhancing SOM (Selayu Garvizu 2000). Use of cover crops that include a small grain species was considered preferable, since they produce greater amounts of more recalcitrant residues and may be more effective in improving SOM and minimizing erosion. Selection of annual cover crops was based on seed costs, local seed availability, and familiarity to farmers. Based on this, suggested species including black oats (*Avena strigosa*), foxtail millet (*Setaria italica*), oat (*Avena sativa*), sudan grass (*Sorghum* × *drummondii*), and wheat (*Triticum aestivum L.*) were integrated into the existing vegetable crop rotations. Above-ground biomass accumulation by these cover crops ranged from 4.4 to 7.7 Mg ha^{-1}. Where these cover crops were combined with additions of chicken manure, SOM content increased from roughly 2.1% to 2.7% within the first 2 years of the study (Rietberg 2008). Long-term (40 years) assessment of the cropping system performance using the ROTSOM model [based on the approach for modeling outlined by Yang and Janssen (2000)] SOM values upto 3.5% may be attained, depending on the cropping system, while in the absence of organic amendments, SOM declined to steady-state values around 1.7–1.8% (Rietberg 2008). Although the progress of the expansion of cover-crop-based systems in Uruguay still lags behind by that in Brazil, the proven benefits of such systems and the lack of cost-effective alternatives seem to create a situation that will favor their future use.

3.3.4 Interpretive Summary of Case Studies

In general, the innovation of successful cover-crop-based systems has been relatively successful in Paraná and in Santa Catarina, but relatively unsuccessful in Florida. Attributes that appear to have facilitated the innovation processes in Paraná and Santa Catarina include:

1. Active involvement by farmers in research and dissemination programs
2. Integration of cover crops into production systems without net loss of land or labor resources
3. Informing farmers of the (direct) benefits of cover-crop use
4. Provision of multiple benefits by cover crops
5. Sufficient access to information, inputs, and technologies required for cover-crop use
6. Provision of skills and experience necessary to manage cover crops effectively

In the case of Florida, many of these attributes have been absent. Unlike Florida, in Brazil, suitable cover-crops-based systems for small farms have been developed and successfully implemented in both row crops and vegetable production systems, zero-tillage equipment is readily available, and these technologies are fully integrated into standard production systems (Prado Wildner et al., 2004; Calegari 2003; Landers 2001). Moreover, as indicated before, Florida farmers tend to be more individualistic, may also develop their own technologies to develop a competitive edge, and may not be willing to share these with other farmers. In this region, innovation in cover-crop-based production systems may thus be required to reward of farmers for ecological services provided by cover crops. The growth of certified organic production in Florida and the USA in general may provide a successful example of such a reward. In this case, the US federal government created a labeling and certification standard that provided a reliable market "niche." Within this market, consumers and producers have allowed to set price premiums that adequately reward producers for organic practices. However, provided that energy and fertilizer prices continue to rise, there may be a direct economic incentive for use of cover crops by conventional farmers as well, provided they will have access to suitable information and cost-effective technologies that can be integrated into their existing systems.

In Canelones, the innovation of cover-crop-based systems remains in an early development stage. In this region, experiences in Paraná and Santa Catarina may provide appropriate development models for implementation of cover-crop-based systems. However, use of system analysis tools such as ROTAT may actually be critical to speed up to technology development and adaptation process since they can provide a systematic structure to streamline the exploration of viable cover-crop-based alternatives to the existing conventional rotations. In this manner, land use options could be evaluated rather effectively, and a limited number of viable alternatives were then further refined during the on-farm testing and development stage. Farmer involvement and participation during system design and development of suitable management options varied from proactive to more passive assimilation of new technologies. Similar to Paraná and Santa Catarina, farmers who joined the project during its inception stage played a critical role during the technology adaptation and transfer processes, and their contributions seem to be invaluable to enhance the regional impact and momentum of technological innovations. Currently, pilot farmers have assumed ownership of new technologies and provided leadership during field demonstrations.

3.4 Conclusion

It is concluded that cover crops can contribute to resource conservation and may provide a viable production option for resource-limited production systems, provided they fit into underutilized niches in the existing agroecosystems. Based on experiences with functional networks within local farm communities (e.g., campesino-to-campesino system), efficient technology transfer of cover-crop-based systems may occur spontaneously with a minimum requirement of external intervention and/or support structures. This development model can foster local development in regions where traditional local social networks favor such an approach. However, in other regions, more extensive interventions may be needed. In this case, the use of co-innovation approach may provide a viable option since it integrates both "science-based intervention" with "farm-based" technology adaptation mechanisms. In this manner, current systems characteristics, challenges and constraints can be mapped out more effectively and models are being used to explore and design desirable development tracks. The use of simulation models to harness some of the complexity of agroecosystems is particularly relevant for cover-crop-based systems. Such an approach may greatly facilitate system design (e.g., development of suitable rotations), assessment of both short-term dynamics (e.g,. nutrient synchronization) and long-term impacts (e.g., SOM trends as effected by erosion), and exploration of different development scenarios, e.g., system performance under different climate change scenarios.

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