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Ecosystem Services Provided by Agroecosystems: A Qualitative and Quantitative Assessment of this Relationship in the Pampa Region, Argentina

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Abstract The development of an analytical framework relating agricultural conditions and ecosystem services (ES) provision could be very useful for developing land-use systems which sustain natural resources for future use. According to this, a conceptual network was developed, based on literature review and expert knowledge, about the functional relationships between agricultural management and ES provision in the Pampa region (Argentina). We selected eight ES to develop this conceptual network: (1) carbon (C) balance, (2) nitrogen (N) balance, (3) groundwater contamination control, (4) soil water balance, (5) soil structural maintenance, (6) N_2O emission control, (7) regulation of biotic adversities, and (8) biodiversity maintenance. This conceptual network revealed a high degree of interdependence among ES provided by Pampean agroecosystems, finding two trade-offs, and two synergies among them. Then, we analyzed the conceptual network structure, and found that both environmental and management variables influenced ES provision. Finally, we selected four ES to parameterize and quantify along 10 growing seasons (2000/2001–2009/2010) through a probabilistic methodology called Bayesian Networks. Only N balance was negatively impacted by agricultural management; while C balance, groundwater contamination control, and N_2O emission control were not. Outcomes of our work emphasize the idea that qualitative and quantitative methodologies should be implemented together to assess ES provision in Pampean agroecosystems, as well as in other agricultural systems.

Keywords Ecosystem services · Pampean agroecosystems · Conceptual network · Expert elicitation · Literature review · Bayesian Networks

Introduction

Over the past few years, the study of ecosystem services (ES) has emerged as a new research area due to its great importance for survival of life on Earth. In this sense, the need to preserve, through good practices, the provision of ES that are directly linked to agriculture is recognized (Barrios 2007; Egoh et al. 2008). Robertson and Swinton (2005) acknowledged the importance of interdisciplinary research for developing agricultural systems which maintain ES provision considered important by humanity (i.e., food, fiber, energy, or wood). Despite the fact that many publications have placed this topic at the forefront of science, there are still unresolved issues. Some of them are the need for a proper methodology of ES provision assessment for dealing with the relative lack of independence or the frequent non-linear relationships among ES (Cork et al. 2001; Heal et al. 2001; Pereira et al. 2005). These issues could be summarized in a framework relating agricultural management with ES provision in agroecosystems (Swinton et al. 2007).

Interdependence is the dynamics of being mutually responsible and sharing a common set of principles with others (Dimuro Peter 2008). Within an analytical

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framework, two mechanisms can cause interdependence among ES: (1) direct interactions (i.e., logical connections between ES), and (2) indirect interactions (i.e., ES connections mediated by an independent driver) (Bennett et al. 2009). These drivers could be natural or human-induced factors which directly cause a change in an ecosystem process (MEA 2005). Moreover, direct and indirect interactions may be opposed (i.e., trade-offs) or not opposed (i.e., synergies) (Bennett et al. 2009). ES trade-offs arise when the provision of one ES is enhanced at the cost of reducing the provision of another ES, while synergies arise when two or more ES are enhanced simultaneously (Raudsepp-Hearne et al. 2010). Several authors have observed trade-offs and synergies in different study systems (Enfors et al. 2008; Chisholm 2010; Raudsepp-Hearne et al. 2010). According to these studies, each ES should not be analyzed in an isolated way but as a set of different elements and processes of an interrelated whole (Cumming and Peterson 2005).

Traditionally, ES assessment has been based on proxy variables (i.e., land-cover/land-use) in order to represent ecosystem processes and provide maps of ES (Seppelt et al. 2011). This approach is tended to be restricted to few input variables with poor quantification of uncertainty, and a reduced capacity for fitting into iterative and adaptive management approaches (Pollino et al. 2007). In agroecosystems, the complexity derived from ecological, economic, and social aspects may hinder the understanding and modeling of the linkages between such interactions (Nicholson et al. 2009). A proper analytical framework should be considered in order to increase the understanding of the ecology behind ES provision and, in turn, the presence of uncertainty in ecosystem dynamics (Carpenter and Folke 2006; Thompson et al. 2007). Furthermore, this approach should be useful for identifying both environmental and management conditions that may compromise ES provided by agroecosystems.

A statistical tool that could meet the ES modeling needs described above is Bayesian Networks (BNs). In general terms, BNs are able to capture the structural aspects of a decision problem as well as serve as the framework for its efficient quantitative analysis (Dorner et al. 2007). They are a graphical representation of a joint probability distribution over a set of statistical variables (van der Gaag and Helsper 2002), and their outcome assesses how probable events are and how these probabilities change due to external interventions (Pollino et al. 2007). This methodology has many advantages over classic expert systems based on rules (e.g., fuzzy logic) generally used for decision making (Kristensen and Rasmussen 2002). The major benefit is the obtention of explicit models, consistent and reproducible as their internal logic can be modified based on available information at any time (López Puga et al. 2007; Low Choy et al. 2009). For these reasons, BNs are used in ecology and wildlife management to depict environmental and management influence on ecological-response variables (Marcot et al. 2006; Uusitalo 2007).

Pampean agroecosystems (Argentina) have been subjected to a high rate of change in their ecological structure and functionality over the last decades (Satorre 2005). Agricultural production and intensification facilitated the generalized adoption of input oriented (i.e., machinery, fertilizers, and pesticides) and process-oriented (i.e., management systems with a high component of information and knowledge such as no-tillage or precision agriculture) technologies (Manuel-Navarrete et al. 2009). As an example, almost 90 % of productive land is under no-tillage (Manuel-Navarrete et al. 2009). These changes have resulted in the development of tools to assess the ES provision level in certain ecological and spatial conditions within the Pampa region (Viglizzo et al. 2006; Laterra et al. 2011). Therefore, it is imperative to have a framework of objective analysis of ES provided by Pampean agroecosystems, explicitly covering their quantification for decision making. Based on these antecedents, the aims of this paper were to: (1) develop a conceptual network, based on literature review and expert knowledge, about the functional relationships between agricultural management and ES provision in the Pampa region (Argentina); (2) demonstrate the presence of interdependence among ES through the conceptual network developed; (3) characterize the structure of the conceptual network in order to identify those variables that better explain ES provision in agroecosystems; (4) parameterize the conceptual network through the probabilistic methodology called BNs; and (5) assess ES provision level under two land-use scenarios (soybean vs. maize) during 10 growing seasons (2000/2001–2009/2010) in the Pampa region.

Materials and Methods

Study Region

The qualitative ecosystem description relating agricultural management and ES provision was designed for the Pampa region, which is located on a more than 52 million ha plain in the center-east of Argentina (Hall et al. 1992) (Fig. 1). Mean annual temperature ranges from 10 to 20 °C and annual rainfall from 400 to 1,600 mm, decreasing from the northeast to the southwest, and soil types are mainly Mollisols (Soriano et al. 1991). The major crops in the region are: soybean (*Glycine max* (L.) Merr.), maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and sunflower (*Helianthus annus* L.). While the Pampa region is generally considered physiognomically and topographically uniform,

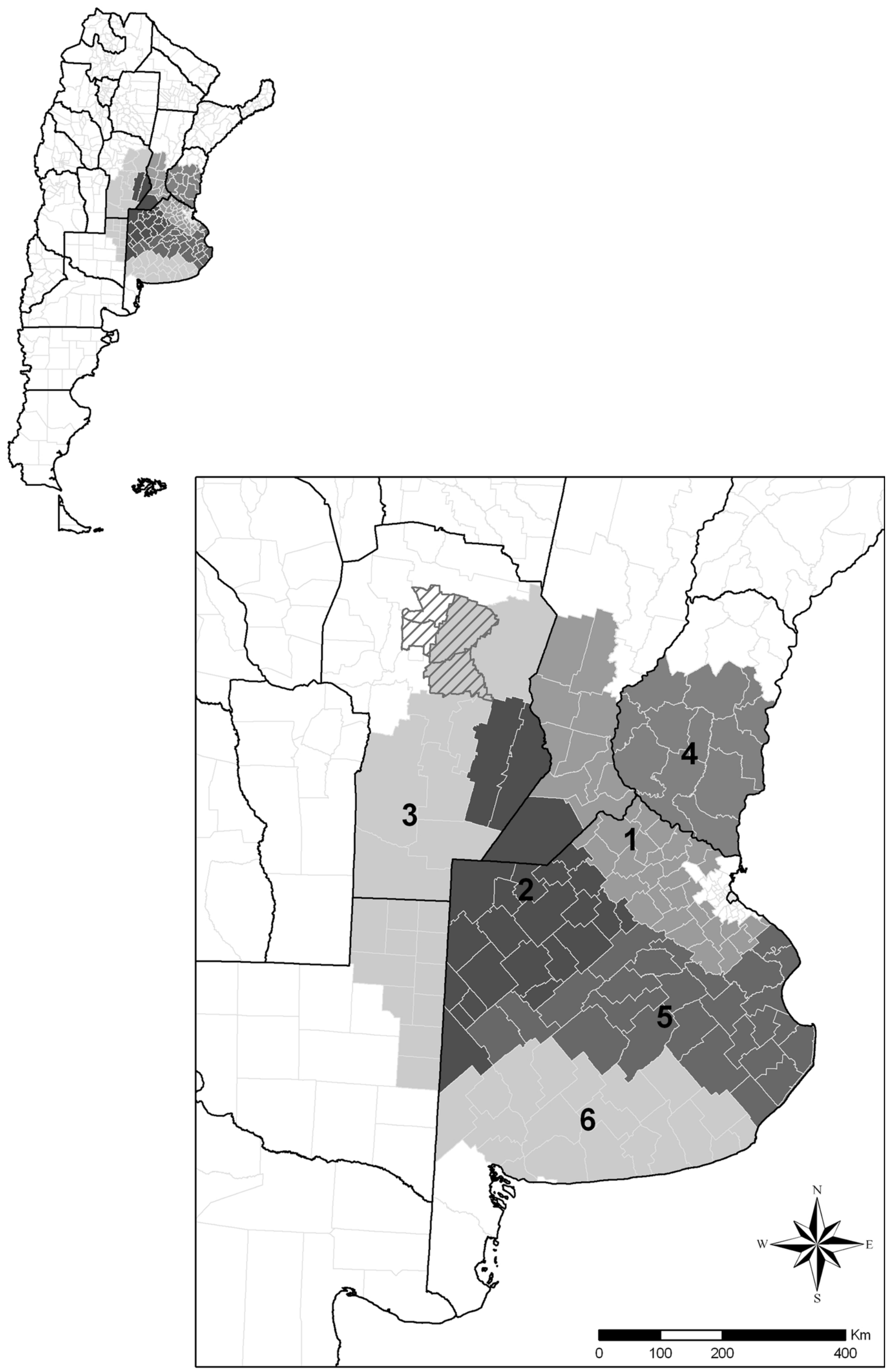

Fig. 1 Location of the Pampa region (Argentina) and its sub-regions: *1* Rolling Pampa, *2* Inland Pampa, *3* Semiarid Pampa, *4* Mesopotamic Pampa, *5* Flooding Pampa, and *6* Southern Pampa. The qualitative ecosystem description relating agricultural management and ES provision (i.e., conceptual network) was designed for agroecosystems of the entire Pampa region. The quantitative ecosystem description of this relationship was designed for those agroecosystems located in the transitional region between the Semiarid Pampa and the Chaco region (see striped area)

various sub-regions are recognized, based on their geomorphology, geology, physiography, soils, and vegetation (Soriano et al. 1991). These sub-regions are: Rolling Pampa, Inland Pampa, Flooding Pampa, Southern Pampa, Semiarid Pampa, and Mesopotamic Pampa (Fig. 1).

The quantitative ecosystem description relating agricultural management and ES provision was designed for those agroecosystems located in the transitional region between the Semiarid Pampa and the Chaco region (see striped area in Fig. 1). In this transitional zone, environmental characteristics correspond to the Semiarid Pampa while vegetation characteristics resemble those in the Chaco region. In the last 20–30 years, this agroecosystem was predominantly a livestock zone. But with agriculture expansion and the shift of the isohyets (i.e., average rainfall is around 750 mm), this zone converted its production from livestock to agriculture. Therefore, these cropping systems are new, and their conditions are relatively marginal for

Table 1 Classification of ES provided by Pampean agroecosystems described in this work (adapted from MEA 2005)

ES group	Specific ES	Sub-category of ES	ES provision indicator
Supporting services	Elements cycling	C balance	C content in soil
		N balance	Available N in soil
	Water cycling	Soil water balance	Water supply for crops
	Soil conservation	Soil structural maintenance	Soil structural stability
Provisioning services	Food provision	Crop production	Crop yield
Regulating services	Climate regulation	N_2O emission control	Denitrification
	Water purification	Groundwater contamination control	NO_3 concentration in groundwater
	Regulation of biotic adversities	[a]	Natural pest mitigation
Biodiversity	Biodiversity maintenance	[a]	Species richness

[a] The ES provision indicator shows a straightforward link to the specific ES

crop production. Even though land-use capability (i.e., potential land-use) of the study area is mostly within the marginal agricultural class, the cropping area in this region is greater than 56 % (Cruzate et al. 2008).

Selection of ES Provided by Agroecosystems

We restricted our study to those ES provided by agroecosystems, and used the Millenium Ecosystem Assessment (MEA) (2005) classification for them. Considering that these systems provide a wide variety of ES, we focused on: (1) carbon (C) balance, (2) nitrogen (N) balance, (3) soil water balance, (4) groundwater contamination control, (5) soil structural maintenance, (6) N_2O emission control, (7) regulation of biotic adversities (i.e., this ES is related to biological control of pests, diseases, and weeds), and (8) biodiversity maintenance (Table 1). In MEA classification (2005), biodiversity is not included explicitly as an ES, but genetic resources are considered as a provisioning service. Zhang et al. (2007) and Stallman (2011) have classified biodiversity as a supporting service, while Dale and Polasky (2007) as a regulating service. Taking this into account, we decided to include biodiversity as an isolated category which supports and provides for the remaining ES.

The ES selected are closely related to significant ecological structures and functions in agroecosystems, and have also been identified as indicators of their status and future trends (Björklund et al. 1999; Viglizzo et al. 2003; Dale and Polasky 2007; Sandhu et al. 2007; Swinton et al. 2007). Their main beneficiaries are both stakeholders and humanity as these ES both increase goods and reduce air and water contamination.

Development of a Conceptual Network Relating Agricultural Management and ES Provision

Firstly, an extensive literature review was made to assemble available knowledge about the qualitative relationships between agricultural management and ecosystem processes involved in determining ES provision. After obtaining this information, we built a preliminary conceptual network for each ES in order to facilitate its further interpretation and analysis during an elicitation process (see paragraphs below). The graphical form of a conceptual network comprises a set of random variables represented as nodes and linked through directed arrows to one or more variables (McCloskey et al. 2011). The eight conceptual networks developed in this work contained five types of nodes: (1) *decision variables*, as those decisions taken by stakeholders at any time of the production cycle (e.g., genotype selection, fertilization regime); (2) *input variables*, as those environmental variables that are inherent to the study region; (3) *state variables*, as those that describe the state of the system; (4) *ecosystem processes*, as those successive stages that take place in ecosystems; and (5) *ES provision indicators,* as those variables which reflect the ES provision level. The logical links between nodes were: (1) *affect*, when there is no certainty as to whether the relationship between two nodes is either positive or negative; (2) *increase*; (3) *reduce*; and (4) *determine*, when one variable originates another variable (e.g., crop species determine crop residue). These logical links appeared only in the individual conceptual networks (see Supplementary material 1), but they were not later included into the general conceptual network (see "Structural Analysis of the Conceptual Network" section) in order to make the discussion straightforward. The development of each conceptual network was made using Visual Understanding Environment software (VUE) (Tufts Academic Technology 2008).

Secondly, we carried out an elicitation process [i.e., the process of extraction and registration of knowledge (James et al. 2010)] in order to check the semantic validity of each conceptual network by presenting it to external experts who are considered reliable (Dibie-Barthélemy et al. 2006). This elicitation process was based on structured interviews where the content and order of events are predetermined by the interviewer (Cooke 1994). An interview was designed in order to be presented individually to the experts. The experts considered were researchers involved in activities related to: (1) crop fertilization, (2) environmental contamination by fertilizers, (3) nutrient dynamics in agro-ecosystems, (4) quality and groundwater contamination, (5) soil fertility, (6) weed eco-physiology, (7) greenhouse gases emissions, and (8) biotic adversities. Researchers were selected within the Faculty of Agronomy, University of Buenos Aires, Argentina (FAUBA). During the interview, we asked these researchers to recommend other colleagues in their same research area but not belonging to FAUBA, to both expand the number of experts to interview and to avoid the bias of information. Taking into account these constraints, we obtained an interdisciplinary expert panel of 20 researchers.

Two Delphi technique rounds were applied to the expert panel (Dalkey and Helmer 1963). The Delphi technique seeks to obtain the degree of consensus among specialists about a given problem, rather than leaving the decision to a single expert (Pérez Andrés 2000). During both rounds, each conceptual network was reformulated in order to reach expert consensus on: (1) the validity of the classification of each node (i.e., decision variable, input variable, state variable, ecosystem process, and ES provision indicator); (2) the inclusion or omission of new nodes; and (3) the validity of logical connections among nodes. During the first round (July–December, 2009), each expert from the expert panel reviewed between 2 and 3 conceptual networks; thus, each conceptual network was reviewed at least by 6 experts. In Delphi methodology, the greatest benefits are obtained with the first 3–4 experts interviewed and then the information tends to be recurrent or redundant (Clemen and Winkler 1999; Winkler and Clemen 2004). This is the reason why during the second round (September–December, 2010), we selected 9 out of the 20 experts previously interviewed and each conceptual network was re-checked solely by 3 experts. The selection of this second group of experts was determined mainly considering the time period they had spent researching on their subject matter (Cornelissen et al. 2003). The main criterion used to obtain the final conceptual network configuration corresponded to a minimum value (75 %) of consensus among experts from the same conceptual network and the same round of interviews about the validity of nodes and connections among them. In cases where consensus was not reached during the first round, the interviewer had to select the most appropriate option and it had to be validated in the second round of interviews (Léger and Naud 2009). In both rounds, each interview lasted approximately 1 h and a half and the interviewer was always the same for all the experts interviewed (F.R.).

Structural Analysis of the Conceptual Network

Once the final version of each conceptual network was obtained, we unified them into a general conceptual network in order to analyze the importance of nodes within its structure (i.e., its "topological importance") (Pocock et al. 2011). As we were interested on the linkage description on final nodes (i.e., ES provision indicators), we included input variables, decision variables, state variables, and ecosystem processes into the structural analysis. This analysis was performed using UCINET 6 (Borgatti et al. 2002). UCINET is an analytical tool applied within the social networks field which can also extend its scope to conceptual networks from other study fields (Stephen Borgatti, e-mail communication). We based our analysis on two network metrics:

(1) Freeman degree (or degree centrality), is the number of nodes to which a particular node is attached (Freeman 1978). Freeman degree formula is as follows:

$$K_i = \sum_j a_{ij} \quad (1)$$

where K_i is the number of links or relationships that node i has, and a_{ij} is the relational component between node i and node j. This indicator highlights those nodes that play a key role within the general conceptual network. Two types of Freeman degree are known: OUT and IN. The first one corresponds to the links which go out from a node, and the second one refers to the links that come to a node. In this work, the analysis was performed using OUT-Freeman degree (OUT-FD) because we were interested in recognizing those nodes directly influencing other nodes.

(2) Bonacich power (BP). This indicator is a modification of Freeman degree approach considering the power of a node in a conceptual network. The original degree centrality approach argues that actors who have more connections are more likely to be powerful because they can directly affect a larger number of other actors, but having the same degree centrality does not necessarily make actors equally important (Hanneman and Riddle 2005). That is, power does not equal centrality in conceptual networks (Cook et al. 1983). BP is calculated as follows:

$$\mathrm{BP} = c(\alpha, \beta) = \alpha(I - \beta F)^{-1} F_i \quad (2)$$

where c is a vector of node centralities, α is a scale used to normalize data, β is the attenuation factor, F is the adjacency matrix, i is a vector of columns of 1, and I is the identity matrix. In order to analyze a conceptual network with BP, it is necessary to select an attenuation factor or β parameter. The β parameter reflects the degree to which a node's status is a function of the statuses of those to which it is connected (Bonacich 1987). Where β parameter is negative (between 0 and -1), being connected to nodes with fewer connections makes a node powerful. If $\beta = 0$, the results equal those obtained with degree centrality. Where β parameter is positive (between 0 and 1), being connected to nodes with more connections makes a node powerful (Hanneman and Riddle 2005). We selected $\beta = 1$ because the amount of information available to a node in the network is positively related to the amount of information available to those nodes with which it has contact (Bonacich 1987).

Comparison of ES Provision in Agroecosystems for Two Land-Use Scenarios

Based on the expert panel opinion (i.e., relative importance on the study region), four conceptual networks developed in "Development of a Conceptual Network Relating Agricultural Management and ES Provision" section were selected to be parameterized, and then quantified, through the probabilistic methodology called BNs (see "Description of BNs Methodology" section). These conceptual networks were: (1) C balance, (2) N balance, (3) groundwater contamination control, and (4) N_2O emission control.

We compared ES provision under two different land-use scenarios: soybean versus maize. Soybean is sown from November to May, and maize from September to April. These two scenarios were different in terms of crop yield and N fertilization dose, but irrigation regime was the same for the two land-use scenarios. Environmental variables (i.e., temperature and rainfall) were similar as they share a similar growing season (i.e., summer). These differences and similarities between both land-use scenarios are also observed in other agroecosystems. Quantification, and therefore comparison, was carried out for 10 growing seasons (2000/2001–2009/2010) in those agroecosystems located specifically on the transitional region between the Semiarid Pampa and the Chaco region (see striped area in Fig. 1).

Description of BNs Methodology

BNs are based on Bayes theorem that provides the distribution of conditional probability of event A given event B (i.e., posterior probability or a posteriori), depending on the distribution of conditional probability of event B given A and the marginal probability distribution (MPD) of event A (i.e., prior probability or a priori) (Jensen and Nielsen 2007). Bayes theorem formula is as follows:

$$P(A/B) = [P(B/A) \times P(A)]/P(B) \quad (3)$$

where $P(A)$ and $P(B)$ are prior probability or a priori; $P(A/B)$ is posterior probability or a posteriori; and $P(B/A)$ is conditional probability or *likelihood.*

A BN is obtained through a learning process which is divided into two phases: a structural learning and then a parametric learning (Fernández 2004; Bressan et al. 2009; Malekmohammadi et al. 2009). Structural learning consists of obtaining the BN structure (i.e., the conceptual network). Usually, a BN can be represented visually as a set of nodes connected by direct links. Nodes represent variables and the probability distribution of their possible states, while links represent causal relationships between nodes (Kristensen and Rasmussen 2002). Nodes with no incoming arrows are parent nodes; while nodes with incoming arrows are child nodes (McCann et al. 2006). The number of states (e.g., high/medium/low) of each variable is dependent on the information to be conveyed and the possible values that it can get (Dlamini 2010). Each variable can take different states in order to improve the overall accuracy of the model. Parametric learning aims to achieve the required conditional probabilities of a node (Fernández 2004; Bressan et al. 2009; Malekmohammadi et al. 2009). Each node in the BN is characterized by a conditional probability table (CPT) (López Puga et al. 2007). Child nodes have CPTs which represent combinations of all states and values of their parent nodes, while parent nodes have MPDs which represent the frequencies of each state (Marcot et al. 2006; Chen and Pollino 2012). The sum of probabilities of each row must total 100 %.

In this work, CPTs had between 2 and 3 states in order to keep them tractable and understandable (Dlamini 2010). States were assigned using information collected through a literature review. States from parent nodes are explained in Supplementary material 2. MPDs from parent nodes were populated through (1) management databases provided by Asociación Argentina de Consorcios Regionales de Experimentación Agrícola (AACREA) (a farmers association), and (2) environmental databases provided by Servicio Meteorológico Nacional (SMN) and Instituto Nacional de Tecnología Agropecuaria (INTA). CPTs from child nodes were populated through expert opinion during the second round of interviews (see "Development of a Conceptual Network Relating Agricultural Management and ES Provision" section). Elicitation of distributions employed questions like "What is the probability of state *X* of variable *A* given scenario 1?"; considering that each scenario was the result of the combination of the states of the parent nodes. Simplification of the elicitation process can be performed by restricting "the amount of conditioning factors to a very low number of variables by restructuring the model" (Uusitalo 2007). For example, this can be done by divorcing nodes; that is, aggregate some nodes by adding a new node which summarizes them

(Chen and Pollino 2012). In this sense, five variables present in the conceptual network of groundwater contamination control were considered as parent nodes of two new variables. Soil factors joined soil texture and soil organic matter (SOM); while irrigation, fertilization, and rainfall were joined in environmental and management factors. Both soil factors and environmental and management factors connected directly to NO_3 leaching risk.

As well as populating CPTs, experts classified their own level of expertise along a scale from 1 to 10 according to the requested information (Borgatti and Carboni 2007; Ferraro 2009). In order to obtain the final probability of each state, we applied a weighted average between each state value and the expertise level of each expert interviewed. The weighted average formula is as follows:

$$x = \sum wX / \sum w \qquad (4)$$

where x is weighted average; X is probability; and w is expertise level of each expert interviewed.

Development and handling of the four quantitative models were performed using Netica Bayesian Network Software (Norsys Software Corp. 2009). A sensitivity analysis was performed for every model using the "Sensitivity to findings" function. Through the process of sensitivity analysis, it was possible to identify those variables that have the most influence on each ES provision indicator along the 10 growing seasons using the mutual information values (Dlamini 2010). The mutual information is a measure of the magnitude with which a finding at one node (i.e., the varying variable) is expected to alter the beliefs (measured as entropy reduction) at the query node (i.e., ES provision indicator). The mutual information (I) formula is as follows:

$$I = H(Q) - H(Q|F) \qquad (5)$$

where $H(Q)$ is the entropy of Q before any new findings; Q is the query variable; and F is the varying variable.

Results

Description of the General Conceptual Network

Input variables, decision variables, state variables, ecosystem processes, and ES provision indicators were linked in the general conceptual network (Fig. 2). Causal relationships among nodes (and their logical links) are explained in detail in Supplementary material 1 for each individual conceptual network. Even though we did not develop a conceptual network for an ES called crop production, experts established that crop yield should be incorporated as an ES provision indicator (Table 1; Fig. 2). Six out of nine ES provision indicators affected other ES provision indicator/s (Fig. 2). While available N in soil affects crop yield, C content in soil affects available N in soil, and available N in soil affects denitrification (Fig. 2). Moreover, C content in soil affects soil structural stability, which affects crop yield and water supply for crops (Fig. 2).

Four interactions which entailed ES provision indicators (Table 1) were evidenced in the general conceptual network. In these cases, another variable (i.e., a driver) mediated in the interaction. Fertilization was the driver of available N in soil and NO_3 concentration in groundwater, through NO_3 leaching risk (Fig. 2). Irrigation was the driver of two ES provision indicators: water supply for crops and NO_3 concentration in groundwater, again through NO_3 leaching risk (Fig. 2). Soil structural stability and C content in soil were driven by crop residue (Fig. 2). Finally, crop residue was the driver of soil structural stability and water supply for crops, through runoff and/or evaporation (Fig. 2).

Structural Analysis of the General Conceptual Network

OUT-FD and BP outcomes were represented in a diagram plotted into four squares (Fig. 3). First and third square membership represented nodes with few (<3) out-links and with high (>4.5) or low (<4.5) BP values, respectively (Fig. 3). Meanwhile, the second and fourth square contained those variables which had more than three connections to other nodes and with high (>4.5) or low (<4.5) BP values, respectively (Fig. 3). Almost all input (Fig. 3a) and decision (Fig. 3b) variables were in the third square. Temperature, microbial biomass, and soil texture had OUT-FD = 2; but they showed different BP values (Fig. 3a). For example, temperature had BP = 4.4 while soil texture had BP = 1.5 (Fig. 3a). This pattern was also observed for variables with OUT-FD = 1 (Fig. 3a, b). Crop species had OUT-FD = 2 and BP = 8.1 while irrigation had OUT-FD = 4 and BP = 3.4 (Fig. 3b). All ecosystem processes were in the third square (results not shown graphically). In the case of state variables, SOM had OUT-FD = 1 and BP = 4.4 while crop residue had OUT-FD = 5 and BP = 5.6. The other state variables (i.e., soil temperature, beneficial species, species composition, and abundance of plant and animal community) had OUT-FD = 1, but different BP values (1.6, 1.6, and 0.6, respectively) (results not shown graphically).

ES Provision Assessment through BNs

ES provision level for the 10 growing seasons analyzed differed according to each ES provision indicator and each land-use scenario. In order to improve the legibility of the four BNs results, we showed the ES provision indicator states

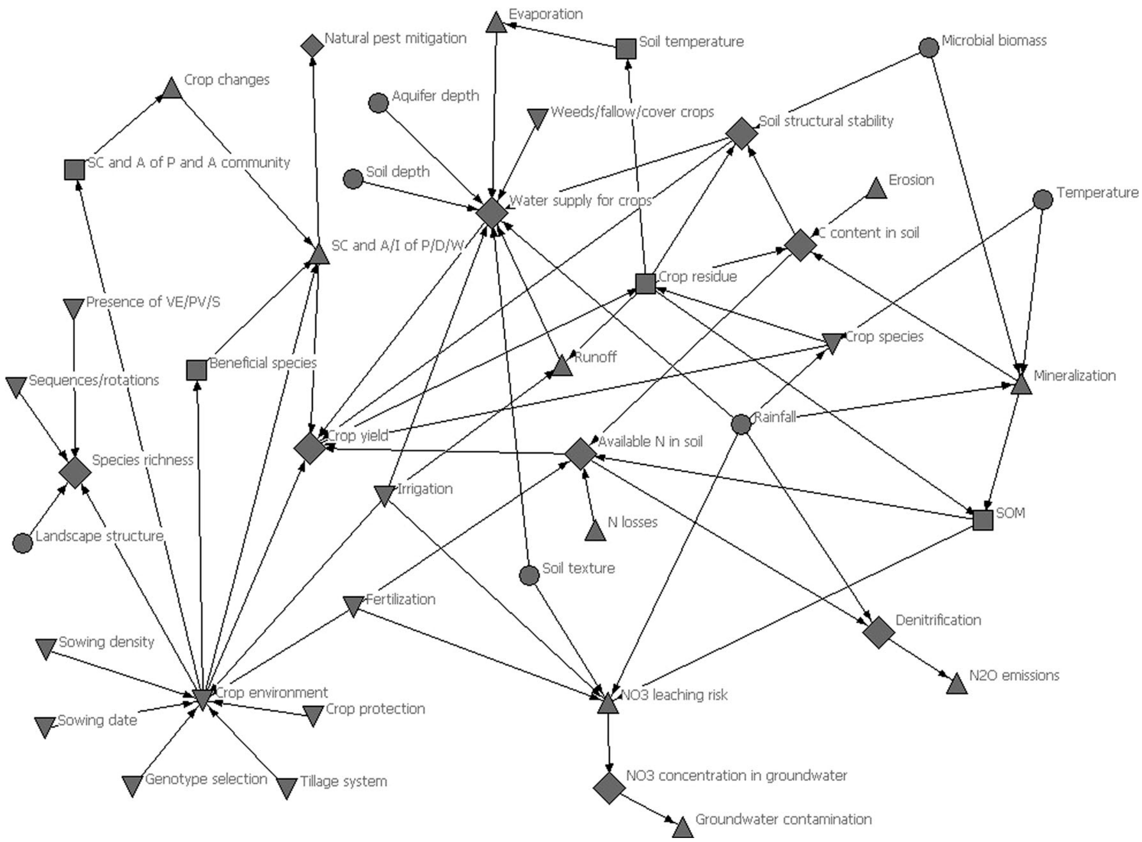

Fig. 2 General conceptual network relating agricultural management and ES provided by Pampean agroecosystems. Legend: *circles* represent input variables, *down-triangles* represent decision variables, *squares* represent state variables, *triangles* represent ecosystem processes, and *diamonds* represent ES provision indicators. *Presence of VE/PV/S* Presence of vegetated edges/permanent vegetation/shelters, *SC and A of P and A community* Species composition and abundance of plant and animal community, *SC and A/I of P/D/W* Species composition and abundance/incidence of pests, diseases and weeds; *SOM* Soil organic matter

more related to agroecosystems sustainability, namely: (1) *High* C content in soil, (2) *High* available N in soil; (3) *Low* NO_3 concentration in groundwater; and (4) *Low* denitrification (Fig. 4). Results for the three states of each ES provision indicator are shown in Supplementary material 3. In soybean, *High* C content in soil ranged between 35 and 45 %; while in maize, it ranged between 60 and 75 % (Fig. 4a). In soybean, there were two falls during 2003/2004 and 2008/2009 (Fig. 4a). These two falls were not so marked in maize, which also had falls during 2000/2001 and 2006/2007. *High* available N in soil (Fig. 4b) had a similar response to *High* C content in soil for both crops. In soybean, *High* available N in soil ranged between 15 and 18 %; while in maize, it ranged between 18 and 22 % (Fig. 4b). Both crops had the same response pattern for *Low* NO_3 concentration in groundwater and *Low* denitrification (Fig. 4c, d). Probability values ranged between 45–55 and 60–85 %, respectively (Fig. 4c, d). Both ES provision indicators showed two falls during 2000/2001 and 2006/2007 for soybean and maize (Fig. 4c, d).

"Sensitivity to findings" results indicated that mineralization rate ($I = 0.093 \pm 0.05$) during five growing seasons (i.e., 2000/2001, 2002/2003, 2003/2004, 2006/2007, and 2007/2008) and crop residue ($I = 0.089 \pm 0.04$) during the remaining years had the strongest influence on C content in soil for maize. For soybean, crop residue ($I = 0.23 \pm 0.03$) and crop yield ($I = 0.11 \pm 0.04$) had the strongest influence along the 10 growing seasons. For maize and soybean, SOM (maize: $I = 0.19 \pm 0.008$; soybean: $I = 0.22 \pm 0.01$) had the strongest influence on available N in soil along the 10 growing seasons. For soybean, crop residue ($I = 0.048 \pm 0.008$) also influenced available N in soil for the whole time period. For both crops, NO_3 leaching risk (maize: $I = 0.88 \pm 0.01$; soybean: $I = 0.73 \pm 0.34$) was the main variable which influenced NO_3 concentration in groundwater along the 10 growing seasons. Available N in soil (maize and soybean: $I = 0.2 \pm 0.03$) and rainfall (maize and soybean: $I = 0.041 \pm 0.07$) had the strongest influence on denitrification for the two land-use scenarios.

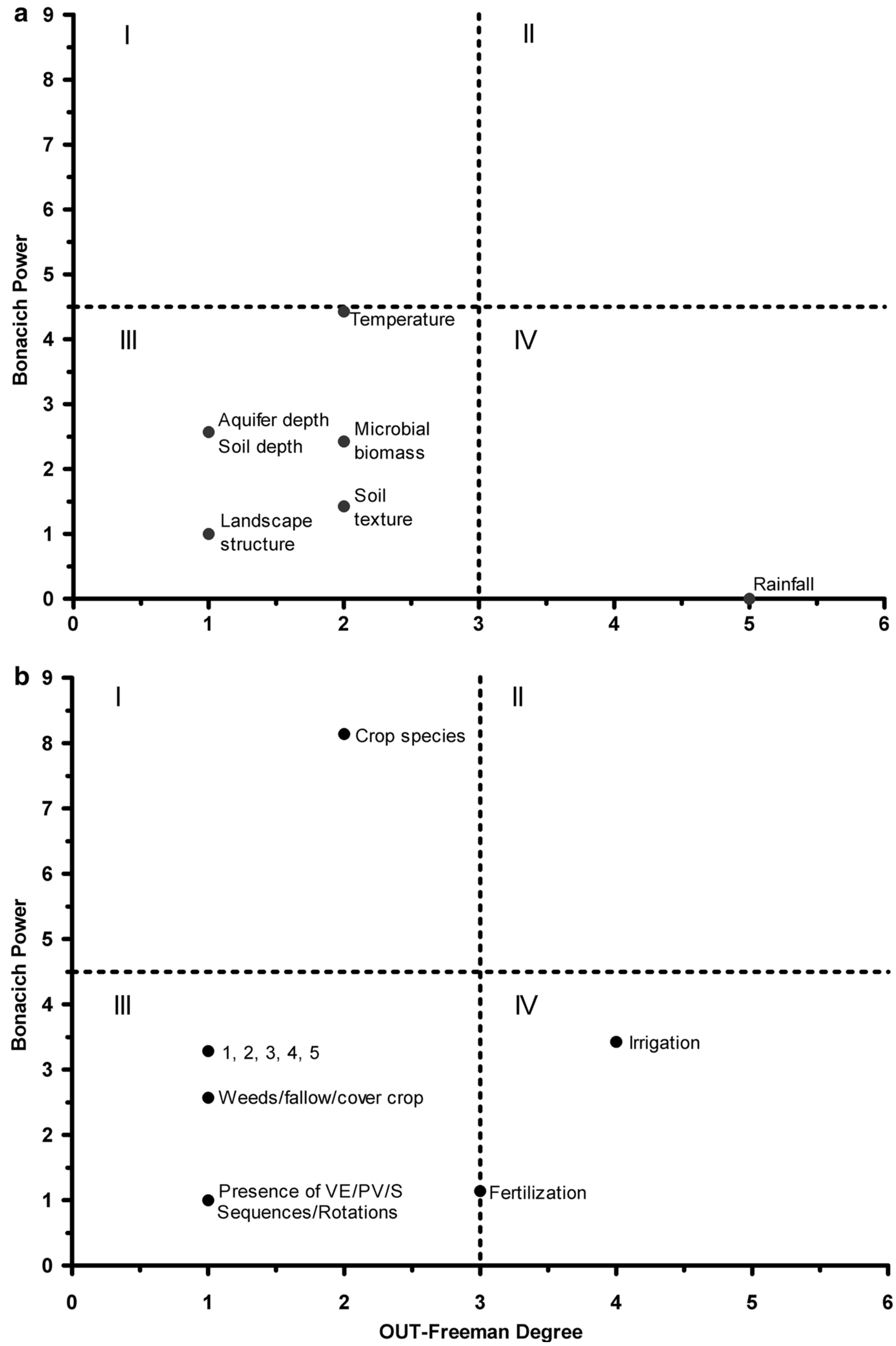

Fig. 3 Relationship between OUT-FD (i.e., number of links which go out from a node) and BP (i.e., power of a node) for environmental (**a**) and management (**b**) variables which form the general conceptual network. Environmental and management variables are considered as input and decision variables in the text, respectively. Both graphs are divided into four squares: *I* Low OUT-FD and High BP, *II* High OUT-FD and High BP, *III* Low OUT-FD and Low BP; and *IV* High OUT-FD and Low BP. Legend: *1* Crop protection, *2* Tillage system, *3* Sowing density, *4* Sowing date, and *5* Genotype selection. *Presence of VE/PV/S* Presence of vegetated edges/permanent vegetation/shelters

Discussion

Three broad areas of research within ecosystem description need improvement: (1) understanding how ecosystems function and how they are affected by human activity, (2) how to inform non-specialists on these modifications in ecosystems, and (3) improving methods for ecosystem evaluation (Gómez-Sal et al. 2003). In this work, we provide in-depth studies of the first and the last aspects. According to this, conceptual modeling is a useful methodology not only when there is an urgent need to qualitatively understand how an agroecosystem operates (Reiter et al. 2009), but also to analyze how they are affected by human practices. To the best of our knowledge, this is the first study in which a conceptual network representing Pampean agroecosystems in terms of their ES provision is shown. The model proposed here is characterized by the integration of the current scientific understanding (i.e., through literature review and experts elicitation) about the relationship between agricultural

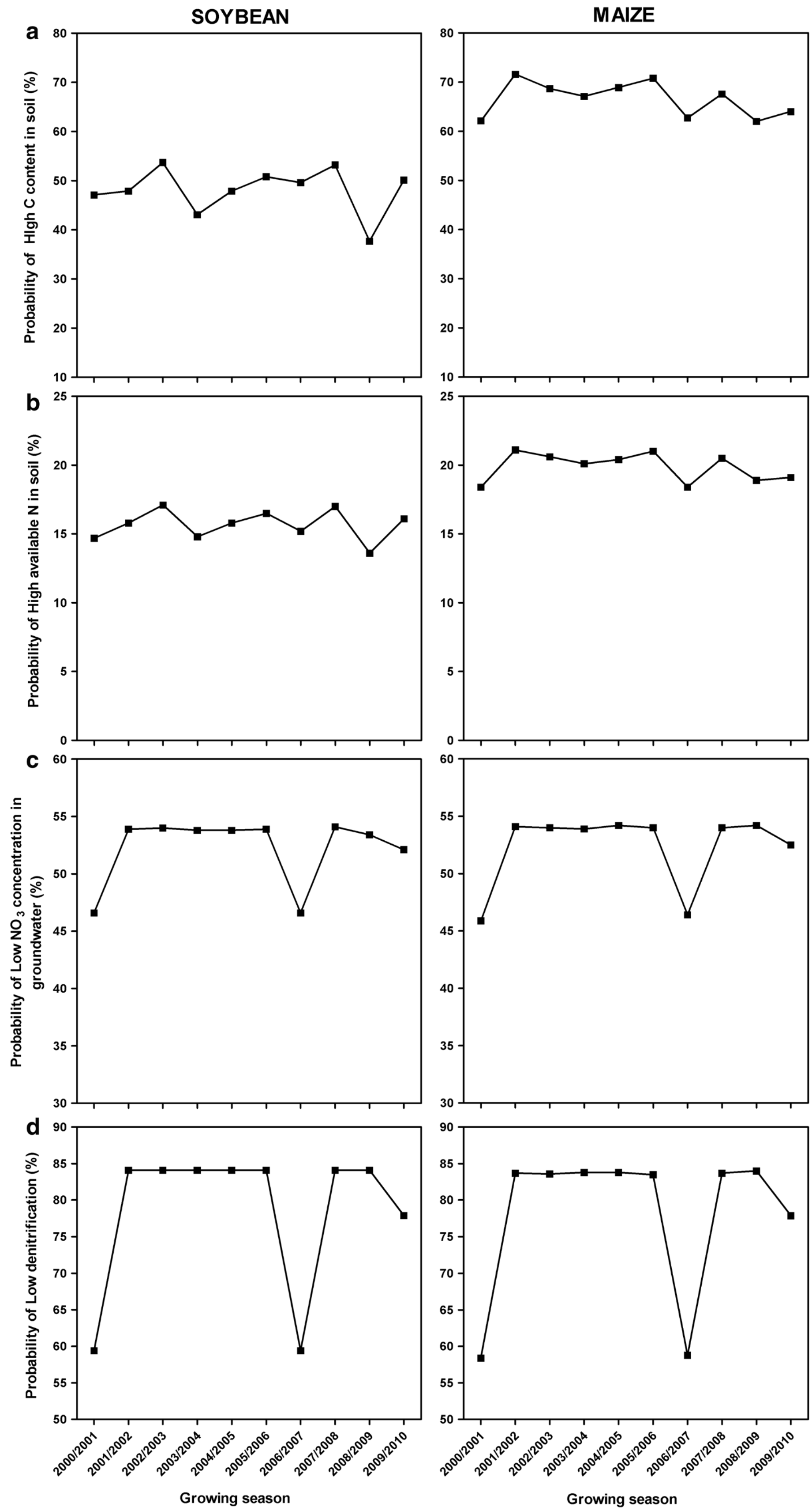

Fig. 4 Provision level of four ES for two land-use scenarios (soybean vs. maize) along 10 growing seasons (2000/2001–2009/2010) in Pampean agroecosystems. These ES are: (1) carbon (C) balance, (2) nitrogen (N) balance, (3) groundwater contamination control, and (4) N_2O emission control. The state more related to agroecosystems sustainability for each ES provision indicator is presented: (1) *High* C content in soil, (2) *High* available N in soil, (3) *Low* NO_3 concentration in groundwater, and (4) *Low* denitrification, respectively. Each state is expressed as a probability (%)

management and ES provision. Furthermore, quantification of a conceptual network can be easily done through novel methodologies such as fuzzy logic (Ferraro 2009) or, in our case, BNs. These mentioned advantages of conceptual networking emphasize the idea that this qualitative methodology should be incorporated into all types of assessments as a tool for describing our understanding of how human and environmental systems work (Gentile et al. 2001).

Direct and indirect interactions were clearly highlighted by qualitatively analyzing ES provision in Pampean agroecosystems through conceptual networking. In the general conceptual network, direct interactions were evidenced among six ES provision indicators (i.e., C content in soil, available N in soil, denitrification, soil structural stability, crop yield, and water supply for crops) (Fig. 2). Indirect interactions mediated by a driver, specifically an external input (i.e., fertilizer use, pest control, and irrigation) (MEA 2005; Bennett et al. 2009), were also found. A relevant aspect is that these indirect interactions raised two trade-offs and two synergies (Fig. 2). On the one hand, trade-offs were directed by decision variables such as fertilization and irrigation. If farmers apply nitrogen fertilizers, the agroecosystem seems to respond in two ways. If available N in soil increases (and assuming that N losses are minimal), N balance is then positive or, at least, equilibrated; but, at the same time, it is possible that NO_3 concentration in groundwater increases and, as a consequence, diminishes groundwater contamination control (or viceversa). The trade-off directed by irrigation could be thought of in a similar way. If irrigation favors soil water balance, it can then negatively affect groundwater contamination control by increasing NO_3 leaching risk. On the other hand, synergies were driven by crop residue (a state variable). Both soil structural maintenance and C balance increase their provision by leaving crop residue on the surface, determining not only a good soil structural stability but also a source of material to be mineralized and incorporated into SOM. Another synergy was found between soil water balance and soil structural maintenance. In this case, crop residue helps to protect soil against moisture loss or disturbances such as water/wind erosion.

In summary, these results clarified the idea that an individual analysis of ES provision would not only be difficult (Zhang et al. 2007), because of the inability to decide whether an item (i.e., in our case, input variable, state variable, ecosystem process, or decision variable) belongs solely to the ES under study; but it would also constitute an insufficient explanation about the relationships among ES. The conceptual framework developed here helped us to determine, in a qualitative way, these possible relationships taking place in Pampean agroecosystems, and we strengthened the idea stated by Bennett et al. (2009) that there is an increasing need for generating this kind of knowledge. In addition, distinguishing direct and indirect interactions, including trade-offs and synergies, could allow us to understand possible differences in ES provision under contrasting agricultural management and to protect them against natural and human disturbances. However, finding trade-offs and synergies seems to be a significant trouble (Viglizzo et al. 2012), particularly when there is no structure which highlights them in an easy way. Additionally, these interactions should be quantitatively analyzed in order to convincingly demonstrate what is truly happening in the system.

In agroecosystems, ES interactions usually arise from management choices made by stakeholders, who can strongly influence the type, relative mixture, and degree of ES provided by these systems (Chapin et al. 2002; Rodriguez et al. 2006). According to the structural analysis of the general conceptual network, temperature, crop species, and irrigation significantly influenced the remaining nodes directly or indirectly, as they showed high BP values (Fig. 3) (Hanneman and Riddle 2005). Although it is considered that agricultural practices are the main modulators of environmental change (Dale and Polasky 2007; Swinton et al. 2007; Zhang et al. 2007; Power 2010), our results evidenced that environmental (i.e., input) and management (i.e., decision) variables did not show a differential pattern of influence on ES provision. A more detailed analysis showed that the highest values of network influence were observed for crop residue (BP = 5.6) and crop species (BP = 8.1), suggesting a close linkage between land-cover/land-use and ES provision (Metzger et al. 2006). In Pampean agroecosystems, as well as in other agricultural regions, the main objective of land-use change is to maximize both provisioning ES (i.e., food, fiber, and timber) and economic benefits (Barral and Maceira 2012).

Agricultural production modifies both the ecosystem functions and structure. Viglizzo and Frank (2006) stated that agricultural expansion and intensification in Pampean agroecosystems are negatively affecting ES provision. In general terms, if agricultural intensification increases, it will erode many ES (Power 2010). However, the range of probabilities encountered for the desirable states from each ES provision indicator (i.e., *High* C content in soil, *High* available N in soil, *Low* NO_3 concentration in groundwater, and *Low* denitrification) did not confirm this claim (Fig. 4). C content in soil did not apparently diminish along the 10 growing seasons. Nevertheless, these results may be masked by the timescale studied, because Caride et al. (2012) analyzed changes in soil organic carbon (SOC) after 60 years with different agricultural management practices in the Rolling Pampa and they showed that SOC content diminished. Low probabilities of *High* available N in soil were evidenced. In general, negative balances between N inputs and outputs are found in Pampean soils because of the relative low fertilizer application which did not completely restore the original high fertility of these soils (Austin et al. 2006; Lavado and Taboada 2009). N losses to the environment were low along the 10 growing seasons, according to some authors who determined that N losses are considerably low in Pampean agroecosystems (Rimski-Korsakov et al. 2004; Álvarez and Grigera 2005). In summary, the only ES provision indicator which highlighted that agricultural practices may be impacting it was available N in soil. Differences and similarities in crop production established more C content in soil and available N in soil for maize, but the same lower amounts of N losses to the environment for the two crops along the 10 growing seasons. These results represent Pampean agroecosystems in terms of their ES provision after particular management scenarios (Paetzold et al. 2010). In this sense, ES provision assessment, both in space and time, is crucial for agroecosystem management (Shiferaw et al. 2005; Paetzold et al. 2010).

Finally, both qualitative and quantitative analyses of certain ecological topics are necessary not only because they can highlight its different aspects, but they can also be complementary, which was the case in this work. Based on the conceptual framework developed, a trade-off between N balance and groundwater contamination control was qualitatively determined. When these two ES were parameterized and quantified through BNs, this trade-off was quantitatively supported. In both land-use scenarios, low fertilizer application to the system determined not only low probability values of *High* available N in soil, but it also determined negative N balances which positively affected groundwater contamination control. That is, NO_3 concentration in groundwater decreased as available N in soil did. It is important to notice that these results positively define the need for qualitative and quantitative methodologies to assess ES provision in Pampean agroecosystems as well as in other agricultural systems.

Conclusions

In order to assess how ES can be affected by agriculture, it is important to gain understanding about the nature of linkages among elements in an agroecosystem through a qualitative analysis. As de Groot et al. (2002) and Carpenter et al. (2009) stated, there is still incipient knowledge about the functional relationships between different agricultural practices and the level of ES involvement. In this study, a general conceptual network was developed to link different variables representing Pampean agroecosystems in terms of their ES provision. Our conceptual framework can be applied to any target agroecosystem, but differences in ecosystem dynamics, variables involved, and relationships among them may require adaptations.

This type of conceptualization is not common in the current ES literature, but it is a good way to illustrate that an ecosystem is quite complex. Moreover, our conceptual network provides: (1) an adequate way to graphically show interdependence; (2) a structure which can be easily parameterized and quantified by a probabilistic methodology like BNs; and (3) a framework which allows decisions to be taken more easily. In this work, we tried to answer the question stated by Cork et al. (2001) of how interdependent ES could be. Although some authors have shown this idea, we think they partially failed in the way they report results. ES provision assessment by BNs emphasizes the idea that qualitative and quantitative methodologies should be complementary. At last, our qualitative structure could modify the perception of stakeholders about the presence and importance of environmental issues and, as a consequence, get a higher degree of adoption of agricultural practices which both respect environment and ES provision (Vignola et al. 2010).

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