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Research article

Application of the theory of planned behavior with agent-based modeling for sustainable management of vegetative filter strips

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ABSTRACT

This study proposes an innovative socio-hydrological modeling framework for the development of environmental policies that are tailored to farmers' attitudes and economic interests but also optimize environmental criteria. From a farmers' on-site survey, a behavior model is developed based on a modified Theory of Planned Behavior (TPB). The dynamics of the social and environmental system is implemented by coupling an agent-based model (ABM) with an agro-hydrological model for vegetative filter strips (VFS). A case study is conducted with farmers from the Larqui river basin, Chile to understand their standpoint on VFS to reduce soil loss in their agricultural fields and protect water bodies. Partial least square structural equation modeling is used to analyze the survey on farmers' aspiration and attitudes. It showed that the constructs added to TPB (behavioral morality, behavioral willingness, knowledge) had a significant effect on modeling the intention and behavior of farmers to have VFS. Based on the survey, the farmers were categorized into perceptive, proactive, bounded rational and interactive agents. An ABM was developed using the behavioral categorization, related decision rules, and utility functions of agricultural activities including the VFS implementation and management. The results of the ABM corroborate with the survey of the farmers. The survey supports the view that the decision on the width of VFS is not solely dependent on the utility generated and the reduction in soil losses but also on the behavior of farmers. This behavioral sociohydrological modeling framework is capable of supporting policy-makers in developing tailored environmental policies that might improve the acceptance of sustainable agricultural practices by farmers.

1. Introduction

In environmental management, the interplay between humans and natural resources is a dynamic system of natural processes and human behavior under institutional and legal boundaries. Environmental management does not only integrate different disciplines but focuses on the interface between humans and nature. The emerging research in socio-hydrology is an example of water resources management (Sivapalan et al., 2012; Di Baldassarre et al., 2015). Coupling human behavior with economic and environmental models is essential in order to develop tailored policies for stakeholders (Jager et al., 2000; Allred and Gary, 2019; Granco et al., 2019; Dessart et al., 2019). In the agricultural sector, there is extensive research on the adoption of technological and environmental innovations and several tools support the evaluation of their impacts on livelihoods and the environment (Berthet et al., 2016; Llewellyn and Brown 2020).

Vegetative filter/buffer strips (VFS) are natural or managed structures at the interface between agricultural land and water bodies. VFS provides multiple benefits and is thus considered as an effective environmental management measure (Lovell and Sullivan, 2006). They remove sediments and pollutants from overland flow (Dillaha et al., 1989; Deletic and Fletcher, 2006), stabilize streambanks (Dosskey et al., 1997), conserve wildlife habitats (Boulet et al., 2003), provide extra yield if they can be harvested (Borin et al., 2010), and they add aesthetic value to the field (Klein et al., 2015). Lowerance et al. (2002) and Abu-Zreig et al. (2004) reported sediment removal of up to 97% in a well-maintained VFS. VFS reduced runoff volume up to 90%, sediment up to 94%, nitrate concentration by 88% and phosphate concentration

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by 95% (Saleh et al., 2017). The trapping efficiency of VFS is majorly influenced by their width (Abu-Zreig, 2001; Akan and Atabay, 2016; Campo-Bescos et al., 2015). The effects of VFS policies, including regulations about their width, need to be examined at the farm and catchment level (Dosskey et al., 2008).

Chile recommends the use of VFS to prevent the movement of eroded soils into nearby waterbodies. However, the use of VSF is only mandatory for forest plantations (Romero et al., 2014) and voluntary in the case of animal farms depending on their environmental licenses (Flores et al., 2010). There is no particular directive for the implementation or protection of VFS in agricultural fields. Developments in other countries show that riparian areas have been converted for crop production with the consequence of conflicts between farmers and environmentalists. Often, measures were later done to restore at least a small VFS. This study investigates if the interplay between the attitudes and behavior of farmers on the one hand, and the natural environment, on the other hand, can be described by a coupled system of a VFS model and an agent-based model (ABM) based on the social theory of planned behavior.

Studying and understanding human behavior is important to comprehend, develop and improve decision-making processes. Neoclassical decision theory assumes that rational actors introduce new technology when the benefits exceed the costs of introduction and that relative prices determine the optimum in the new equilibrium. Simon (1957) extended decision theory with behavioral aspects by introducing the 'satisficing concept' as a base of a new 'bounded rationality' paradigm, which accepts compromise solutions for complex decision problems rather than search for optimum solutions. Recent theories consider psychological and sociological factors that influence decision-making behavior, namely aspirations, risk attitudes, cultural norms and peer group influence (Kahneman, 2003; Weersink and Fulton, 2020). While humans have different individual thinking and behavioral processes, societal and environmental elements also influence decision-making (Miyasaka et al., 2017). Schulze et al. (2017) classified the most influential factors of a human decision-making model as monetary returns, social groups, impact on others, environmental altruism, environmental/non-economic benefits such as aesthetic values or recreation. Human responses with respect to policies that recommend field-level changes require multi-disciplinary knowledge and understanding of not only the policy and the effects of it on the environment but also the effect of the policy's outcome on stakeholders like farmers (Smajgl et al., 2011).

In 1991, Ajzen developed the Theory of Planned Behavior (TPB) as a successor to the Theory of Reasoned Action by Fishbein and Ajzen (1975). He theorized that the likeliness to perform a behavior stems from the strength of the intention, willingness to try and exert effort towards the task at hand (Ajzen, 1991; Suh and Hsieh, 2016). According to TPB, the intention to perform is dependent upon attitude, subjective norm and perceived behavioral control. The simple and efficient framework of TPB makes it easier to analyze behavior from the background information collected on-site in the form of local interactions or in-depth surveys (Russo et al., 2015).

Zubair and Garforth (2006) have studied farmers' behavior to different aspects related to adopting agroforestry practices using TPB. They concluded that TPB provides a structural framework to identify the outcomes based on beliefs, social interaction and behavioral control factors. Cooper (2017) evaluated the application of TPB to ensure compliance with urban water restrictions and concluded that behavioral compliance is significantly influenced by the constructs - attitude, social norms and behavioral control as explained by the TPB model. Caffaro et al. (2019) assessed different paths using which the information environment affects the adoption of sustainable measures by the farmers based on the TPB constructs. They concluded that attitude and perceived behavioral control were the dominant constructs that influenced farmers' behavior. The farmers' decision was not influenced by subjective norms in that study. Understanding the different aspects of behavioral theory can give an insight into the decision-making process of the farmers capturing different dynamics and feedbacks as seen in a socio-ecological system (Liu et al., 2008; Allred and Gray, 2019). Due to the presence of clarity of constructs and correlational confirmation (Skår et al., 2008), TPB is used in the current study.

Agent-based models (ABM) emulate the internal behavior of agents in a system, their interaction amongst each other as well as their interaction with the environment. Enrico Fermi, a physicist in the 1930s incited upon the concept of ABM whilst trying to transport neutrons through matter (Turrell, 2016). However, the very first economic ABM was developed to analyze agents' preference for the location to live by Schelling (1971). The agents and their environment are represented explicitly in ABM, thus modeling local interactions in a straightforward manner (Izquierdo et al., 2019). Internal conditions for behaviors can also be encoded to express real-world conditions (Matthews et al., 2007). The ability of ABM to be analogs of real behavior makes it suitable to model the heterogeneous and complex structure of socio-environmental and socio-hydrological systems. The agent's behavior is modeled using the knowledge extracted from the context information without the use of training datasets. ABM is considered as a decision support tool, through which in an environment an agent's interaction is simulated, which would be expensive to analyze in the real world (Castilla-Rho et al., 2015).

Although the application of ABM was initially used in computer simulations (An, 2012), in recent years, ABM is applied to diverse studies. ABM has been applied for studies involving the farmers' behavior with respect to the application of landscape, economics (Guillem et al., 2015), environmental effects (Heckbert et al., 2010), socio-hydrology (Pouladi et al., 2019), and policy development (Happe et al., 2006; Brady et al., 2012; Granco et al., 2019). One of the prominent merits of using ABM is to deal with public involvement in the representation of scientific formulations in the form of 'soft sentences' that is comprehensible and easily understood by all the stakeholders (Rixon et al., 2007). Rounsevell et al. (2011) discuss the suitability of ABM with qualitative social-survey data. According to Etienne et al. (2002), the analysis of different viewpoints for representing the agent's perception is important in their simulation, to encourage the agents to act collectively. Sengupta et al. (2005) investigated the acceptance of a conservation program by farmers to avoid the cultivation in endangered land due to erosion in exchange for monetary value. The ABM developed in their study is combined with a geographical information system to provide spatial effects of land use policies which are then used in decision-making with the help of a decision tree. Some case studies where an agent-based simulation model has been used in environmental studies have been documented by Hare and Deadman (2004). Therefore, ABM is chosen to be adopted in this study to model farmers' decision-making process in the economic, social and environmental context.

The overall aim of this work is to demonstrate the importance of developing coupled social and technical models based on social behavioral theories when investigating human-environment feedbacks. For this, we follow these main objectives:

(a) Development of a model of farmers' behavior under the social and environmental influence by an empirical survey and an extension of the TPB;
(b) Investigation of environmental and social factors that motivate farmers to keep or implement a certain width of VFS by coupling a VFS model and an ABM;
(c) Discussion of implications for effective agricultural and water policy-making based on results from a case study in Chile.

2. Materials and methods

2.1. Study area

This study has been carried out in the district of Diguillín, which is part of Región de Ñuble in Chile. It has a flat topography with an elevation range of 65–163 m.a.s.l. The catchment is in the upstream of River Larqui between Latitude 36°41' – 36° 48′ S and Longitude 72°16' – 72° 06' W. The basin has an area of 101 km^2. River Larqui receives water from the nearby streams and flows into River Itata. It receives an annual average rainfall of 1000 mm and the mean temperature varies from 20 °C in summer to 7 °C in winter. Volcanic soil is predominant in the region leading to the formation of fertile Bulnes soil (red clay-loam) majorly in the basin. The basin shows strong agricultural activity, mainly based on annual crops, sugar beet, orchards along with meadows, thickets, forests and livestock. The basin experiences soil erosion, reduced crop yields and increased cost of production (Flores et al., 2010). Bonilla and Vidal (2011) have revealed that furrow irrigation systems adopted by farmers can also be one of the factors that hike the rate of soil erosion.

According to Centro de Información de Recursos Naturales (CIREN) report (2010), major parts of the study area experience moderate to light erosion. Moderate soil erosion refers to erosion that has exposed the subsoil surface and, in some cases, results in the formation of grooves. Light erosion refers to the loss of soil that occurs on surfaces with slope and semi-dense vegetation cover of 50–75% that would slightly alter the thickness and texture of the soil. Thus, the conservation and management of VFS are suitable measures to tackle erosion and finally reduce sediment transport in the region.

2.2. Modeling framework

To understand and model the decision-making process of farmers regarding VFS, a socio-hydrological chain of experiments and models is developed as shown in Fig. 1: (i) a field survey is carried out with random sampling method to investigate the field conditions and attitudes of a group of farmers belonging to the Larqui river basin; (ii) the constructs of the TPB are extended for socio-environmental problems and the survey is evaluated using partial least squared structural equation modeling (PLS-SEM); (iii) decision rules and utility functions are developed to describe farmers' behavior and decision processes based on TPB and monetary benefits from agricultural activities and VFS; (iv) an ABM using the NetLogo software is created with decision rules for agents based on their behavioral categorization (v) soil erosion for the full combination of different field classes and widths of VFS is computed by the model VFSMOD-W, the results of which are coupled with ABM to implement human-environment feedbacks; (vi) the results of ABM are evaluated and factors influencing the decision-making of farmers to ensure a certain width of VFS along their fields are examined.

2.2.1. Field survey and behavioral analysis with an extended TPB

For the survey, a population of 120 farmers was identified, who own farms that are adjacent to River Larqui and are registered with The National Irrigation Commission of Chile (Comisión Nacional de Riego, CNR) as consumers of water from River Larqui at the time when the survey was conducted. A simple random sampling method is adopted to collect the survey of 92 farmers, who agreed to participate in the study. The questionnaire focused on farmers who cultivate crops and vegetables on their land. It is inspired by Armstrong and Stedman (2012). In this study, a five-point Likert scale is used which allows the farmers to express how much they agree or disagree with a given statement. The survey is designed to gather information on the agricultural practices of the farmers, their perspective on the environment, water resources and vegetative filter strips. The survey includes questions that support the evaluation of different constructs of TPB to analyze the factors influencing the decision-making of the farmers and is part of supplementary material. It is divided into five sections. The first section contains questions to gather basic information about the agricultural field like size, layout, the crop grown, and irrigation techniques used, etc. The next sections were divided to address questions related to TPB.

The assumptions used in TPB are that human behavior is goal-oriented, influenced by society and peers, and decisions are made with a logical and rational approach (Ajzen, 1985; Sandberg and Conner, 2008). The constructs of TPB are as shown in Fig. 2. Ajzen (1991) defined behavioral intention as 'the amount of effort one is willing to exert to attain a goal'. The intention is steered by the attitude towards the behavior and subjective norm (Menozzi et al., 2015). Subjective norm refers to societal pressure perceived by an individual on whether to perform or not perform the said act (Bijttebier et al., 2018). It refers to the perception of the ability or difficulty that a respondent may face towards executing the behavior. This may be impacted by previous experiences, information received from peers and friends (Ajzen, 1991). Please refer to Ajzen (1991) for detailed information on the development of the original constructs.

To encompass the overall field situation, an extended TPB is used in this study as shown in Fig. 2. Along with the constructs from the basic TPB, three additional constructs are used in this study – knowledge, behavioral willingness and behavioral morality that describe individual norms. One of the key factors that influence behavior and decision-making is knowledge (Michie et al., 2008). The construct knowledge enables to understand environmental, VFS related knowledge the

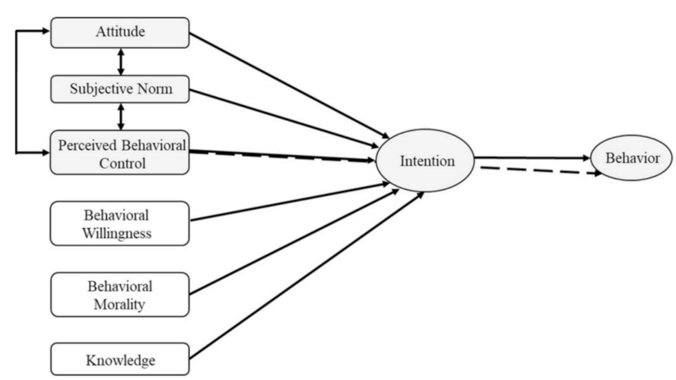

Fig. 2. Extended TPB model (The original TPB model from Ajzen, 1991 is highlighted with a grey background).

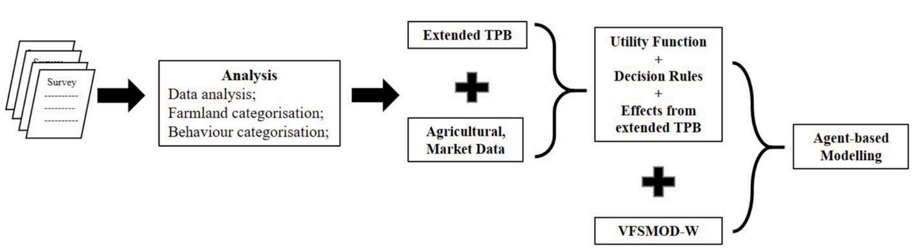

Fig. 1. Schematic representation of the workflow.

respondents have, and the influence it has on the decision-making behavior. The knowledge of VFS and its benefits on water, flora, fauna, reduction of sediment and pollutant transport via overland flow and economy of the farmers are usually known only to environmental/agricultural experts and organizations despite VFS being recommended as one of the best management practices. Introducing the construct knowledge is based on the assumption that farmers do not have this knowledge which is crucial for them to decide on the width of VFS in their agricultural fields.

Gerrad and Gibbons (1997) defined behavioral willingness as 'openness to risk opportunity'. It entails how far the respondent is willing to enact a particular behavior under certain conditions. In this study, this construct is used to find the influencing factors that would motivate the farmers to overcome the existing prejudice to retain and widen VFS. It is assumed that the influencing factors could be the neighbors, association with agricultural organizations, improvements to the environment, an increase of income, monetary compensation, etc. Behavioral morality is another factor that is an integral part of decision-making that has been empirically proven to have a significant effect (Garrigan et al., 2018). With this construct, we attempt to find the thinking of farmers on a personal level about bigger issues of environment, water, their importance, and protection for the future generation. We try to appeal to farmers' determination to safeguard the environment on an individual level. With the inclusion of all the different constructs influencing decision-making, an extended TPB as shown in Fig. 2 is used in this study. The weights of the constructs of the extended TPB provide information to the policy-makers as to which constructs are most important to ensure the widening widths/keeping VFS in the agricultural fields within the basin.

2.2.2. Behavior categorization, development of utility function and decision rules

The farmers are represented as agents in NetLogo with the behavioral change factors implemented in utility functions. The farmers were classified into different types depending on their response to the survey questions to factor in the personality or behavioral category. This classification helps to identify the agents, observe the change in the behavior of the agents, the interaction of the agents amongst themselves and the environment from a socio-economic context. These are important factors as they affect farmers' decision-making (van Dijk et al., 2016). In most of the socio-environmental systems, the agents follow a bounded rational decision or a profit-maximizing decision by taking into account the environmental information. Besides, agents are social learners that imitate other agents (Schlüter et al., 2017). Therefore, the agents in this study are classified as a) **proactive** (having a particular goal to achieve – maximization of profit), b) **perceptive** (pro-environment – cares and is inclined to take actions to safeguard the environment; opt for managed VFS instead of natural), c) **bounded rational** (rational optimizers that act with the limited collected information and also take into account selected neighbor actions) d) **interactive** (communicates with other agents and is easily influenced by neighbor actions). To explain the selection criteria for the different types of agents, the utility function U is defined as,

$$U = P_{UF} + E_{UF} \tag{1}$$

P_{UF} represents the monetary benefit from the agricultural activities and E_{UF} represents environmental benefits in monetary terms from having VFS. E_{UF} is further elucidated as,

$$E_{UF} = [L*W](Incentive_{VFS} + B_e) \tag{2}$$

The incentive ($Incentive_{VFS}$) received for the width of VFS and saving water resources, the long term benefit (B_e) which entails the application of nutrients saved and harvest from VFS would vary depending on the length (L) and width (W) of VFS chosen by the farmer. The monetary benefit from agricultural activities, P_{UF}, is further composed of several terms as elucidated in Eq. (3).

$$P_{UF} = Profit_{AGRI} - Loss_{AGRI} - [L*W]\ Inv_{VFS} - [L*W]\ Mt_{VFS} + [L*W]\ (NP_s + Harvest_{VFS}) \tag{3}$$

$Profit_{AGRI}$ is defined as the profit earned by the farmer from the agricultural field except for the area of VFS, and it is calculated by multiplying the active area (Q) with net income (N) as shown in Eq. (4). $Loss_{AGRI}$ is defined as the loss in monetary value caused by soil loss due to erosion and it is computed in Eq. (5), where SL is the soil loss, N is the income from agricultural production; C_{SL} is the cost of soil losses. P_{UF} also takes into consideration the loss, which the farmer would face in terms of the initial investment, and the cost of annual maintenance of VFS as well as the financial saving done in terms of nutrients saved by VFS and the financial gaining from harvesting the produce of VFS.

$$Profit_{AGRI} = Q * N \tag{4}$$

$$Loss_{AGRI} = SL * N + SL * C_{SL} \tag{5}$$

The different parameters and their values in the utility function for this study are listed in Table 1.

Based on the behavioral types, different decision-making rules are defined with respect to the utility for future actions. It is factored within decision-making rules that some cases of having of VFS may cause negative utility. Therefore, care is taken to ensure that agents do not accept the economic loss and reject a width of VFS if it has a negative impact on their economic situation. Even the perceptive agents who favor increasing the width of VFS would not go ahead with the width that results in a negative income in any of the three years. All the rules for each type of agent classified are tabulated in Table 2.

2.2.3. VFS modeling with VFSMOD-W

Several models can be used to assess the efficiency and

Table 1
Parameters of the utility function.

Parameter	Description	Units	Value	References
Q	Productive agricultural field	m^2	Variable according to the field class	From field survey
L	Length of VFS	m		
N	Net income from the agricultural activity	CLP/yr/m^2	Variable according to the year	FAO (2017)
SL	Soil loss	kg/yr/m^2		From VFSMOD-W
$\mathbf{C_{SL}}$	Cost of soil losses	CLP/yr/kg		Tapia and Villavicencio (2007)
W	Width of VFS	m	[2, 5, 10, 20]	–
$\mathbf{Inv_{VFS}}$	Investment cost (one-time) for implementing VFS	CLP/m^2	58.4	Tapia and Villavicencio (2007)
$\mathbf{Mt_{VFS}}$	Annual maintenance cost	CLP/yr/m^2	103.3	
$\mathbf{NP_s}$	Cost of nutrients saved by VFS	CLP/yr/m^2	1.79	Geza et al. (2009)
$\mathbf{Harvest_{VFS}}$	Profit from harvesting VFS produce	CLP/yr/m^2	6.63	
$\mathbf{Incentive_{VFS}}$	Monetary incentives from the State including water incentives	CLP/yr/m^2	15.4	Artacho et al. (2009) & Geza et al. (2009)
$\mathbf{B_e}$	Long term environmental benefit	CLP/yr/m^2	20.67	USDA Program Aid (2000)

Monetary units expressed in Chilean Pesos (CLP).

Table 2
Decision-making rules for different types of agents.

Type of agent	Basic characteristics	Decision-making Rule
Pro-active agent	Maximize profit	Max U considering W = 2, 5,10 or 20 m
Perceptive agent	Favorable to the environment as long as utilities are positive	Case1: U > 0; new U ≥ 0 change W Case2: U < 0; decrease W to keep U > 0 Case 3: U = 0; retain W
Bounded rational	Favorable to the environment as long as utilities are better, take into account peer influence as well as information collected	Case1: U > 0; new U ≥ U change W Case2: U < 0; decrease W to keep U > 0 Case 3: U = 0; retain W
Interactive	Decision under peer influence but will ensure utilities stay positive	Case 1: new U < U; retain W Case 2: new U > U; change W

characteristics of VFS. VFSMOD-W (Muñoz-Carpena et al., 1999) (https://abe.ufl.edu/faculty/carpena/vfsmod/index.shtml) was selected in this study, as it requires a limited number of input parameters and can be coupled with the ABM in NetLogo. VFSMOD-W is an event-based model that simulates infiltration, outflow, and sediment retention efficiency for VFS of different characteristics (Abu-Zreig, 2001; Dosskey et al., 2002). To simulate soil losses with the VFSMOD-W, a combination of unsteady storm, incoming hydrograph, VFS spatial distribution, and incoming sediment's characteristics have to be introduced. The results of VFSMOD-W include water outflow, infiltration volume and sediment trapping in the VFS amongst other parameters (Abu-Zreig, 2001). Due to the non-availability of hourly precipitation data, UdeC - Chillán station which is approximately 50 km away from the study area is used. For ease of soil loss simulation and incorporation into the ABM, the agricultural fields of the farmers are divided into 6 classes depending on the area. Accordingly, the source area flow path length (Slength) and source area width (Swidth) are defined for each field class. The slope of the source of the area was considered as 1%.

2.2.4. ABM using NetLogo

Modeling the socio-environmental-economic system of how farmers decide on which width of VFS to provide on their farms, depending on the utility incurred by them with active environmental interaction and interaction between the farmers themselves is examined in the current study by an ABM. Each agent represents a farmer who is the owner of a field. Agents are categorized according to their behavioral type as described in 2.2.2. A field is represented as one grid cell, independent of the real size of the field. Each tick represents a single day in the simulation period between 1998 and 2008. It is designed in such a way that, the agents receive information about the soil losses in their fields and the amount of soil retained by the VFS and the current condition at the end of every year as simulated by VFSMOD-W. An internal parameter (Erosion Problems parameter, EPP) is defined and assigned a value of 1 to indicate that the soil losses in a calendar year are greater than the threshold value, else it is assigned 0. A one-time investment is made by perceptive agents to convert the existing natural VFS into managed VFS based on the knowledge of soil erosion and retention by both managed and natural VFS at the start of the simulation based on the response to the survey.

At the end of every three years of simulation (2000, 2003, 2006 and 2009), the agents are asked to analyze the utility generated and a decision is made about the width of VFS for the next three years. This decision is governed by the decision-making rules set for each agent category as described in Table 2. During the simulation period, bounded rational and interactive agents are enabled to exchange information via interaction. At the end of the simulation period, the decision of farmers from each category is analyzed to see what width is chosen by them.

Technically, the ABM was implemented in the NetLogo software developed by Uri Wilensky in 1999 (http://ccl.northwestern.edu/netlogo/). It is a free and open-source software platform with a simplified and flexible programming language (Castilla-Rho et al., 2015). Hence, it is chosen to be used for the current study. For detailed information, the ODD + D protocol developed by Müller et al. (2013) to describe human decision-making in ABM for the current study is provided in supplementary materials.

3. Results and discussion

3.1. Statistical analysis of the field survey and the theoretical model

From the population size of 120 farmers, 92 agreed to participate but 18 farmers did not complete the survey. The resulting sample size of 74 leads to an error margin of 7.1% for the desired confidence level of 95%. The sample size is the upper limit posed by the constraints of the study area and problem even though a smaller error would be desirable. From the analysis of the survey, it is found that 48% of the respondents reported that they use stream water for irrigation (13%-always; 12%-seasonally; 19%-most of the times; 4% -few days) and more than 50% responded that the water quality ranged between bad to extremely bad based on their observation. However, 95% responded that they had buffer strips on their farm. 72 out of the 74 respondents said they had 'natural' vegetation in their buffer and only 1 respondent indicated having a manmade buffer strip. Natural buffers are not taken care of or are managed to ensure erosion reduction and the common response for the question as to why they do have it was that 'it is just there'.

Though in the survey it is seen that 54% of the farmers thought that their land is not affected by erosion, this is taken into account as not having knowledge of erosion as erosion is a gradual process. Since the farmers had very little knowledge about buffer strips in general, they had little knowledge about buffer strip programs and how they operate and are beneficial to them. This is seen with 50% of the respondents' replying 'don't know'; 40% agreeing that VFS is beneficial and 9% disagreeing with the benefits of such programs. From the responses provided by the farmers in the survey, the farmers who were motivated only by the monetary benefits of VFS are classified into proactive agents (11). The farmers that actively wanted to have VFS in their fields and were concerned about water and the environment are classified into perceptive agents (4). The farmers who were aware of the soil erosion in their fields, had knowledge on the quality of water they received and the benefits of the buffer are categorized into bounded rational agents (10). The farmers who were willing to have VFS because of their neighbors or friends are categorized into interactive agents (49).

To analyze the causal relationship of the TPB, structural equation modeling (SEM) was performed using the partial least square (PLS-SEM) method with SmartPLS 3 (https://www.smartpls.com/) (Hair et al., 2014). 15 questions from the survey were used to develop the formative-formative type higher-order construct model using the embedded two-stage approach as shown in Fig. 3. Each item contributes to the formation of the construct and they are not interchangeable, therefore, a formative-formative type model is used in the study. The lower-order constructs of the model are attitude (ATT), subjective norm (SN), perceived behavioral control (PBC), behavioral morality (BM), behavioral willingness (BW) and knowledge (KNO). Intention (INT) and behavior (BEH) are the general higher-order constructs. In the

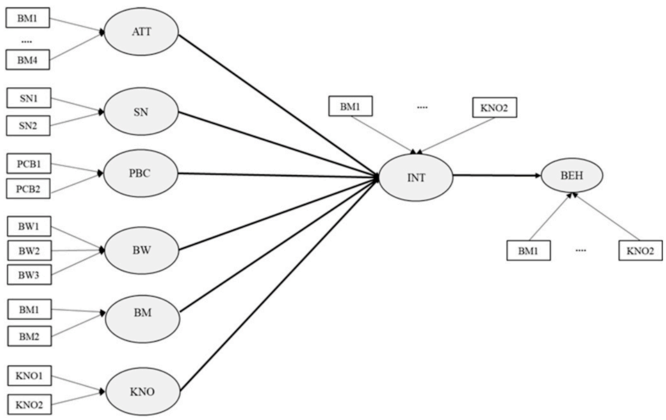

Fig. 3. Formative-formative type model of the extended TPB (embedded two-stage approach).

Table 3
VIF, outer loading, t and p-value of constructs.

Constructs - Items	VIF	t-value	Outer loading	p-value
Attitude		7.482		0
I want to conserve stream for the future generation	1.329	1.62	0.48	
I will be upset if my activities harmed stream	1.833	3.6	0.81	
The stream is the lifeline of the region	1.537	1.32	0.55	
I have benefitted from VFS	1.308	2.01	0.46	
Subjective Norm		0.90		0.367
Neighbors are my close friends	1.468	3.15	(-0.45)	
I will implement VFS if most of my neighbors do	1.899	9.91	0.87	
Perceived Behavioral Control		4.26		0
VFS improves the aesthetics of my property	1.71	1.67	0.79	
VFS improves wildlife habitat in the region	2.028	3.95	0.94	
Knowledge		3.88		0
I have heard about VFS	1.77	5.19	0.91	
I know about stream water quality	1.395	1.73	0.59	
Behavioral Morality		4.84		0
Protecting the environment is important to me	2.199	2.46	0.96	
I have a moral obligation to maintain good water quality	2.041	1.07	0.82	
Behavioral Willingness		7.78		0
I will implement VFS if volunteers plant it	1.592	3.73	0.75	
I will implement VFS for cleaner runoff	1.313	2.76	0.65	
I will if I can plant fruit trees in VFS	1.652	1.04	0.61	

embedded approach, the scores of the lower-order constructs are added as variables to the higher-order constructs.

To validate the formative-formative type higher-order construct, the measurement model is evaluated in a two-step procedure. In the first step, collinearity issues are checked. There are no collinearity issues with the items (questions) of lower-order constructs as the variance inflation factor (VIF) values are all lower than the conservative threshold of 3 as shown in Table 3. In the second step, the test statistic t and its significance p of the indicator outer weights (relative) and outer loading (absolute) are evaluated by running a bootstrap of 5000 samples. Items with significant outer weight ($p < 0.1$) and/or outer loading greater than 0.5 are retained (Hair et al., 2014). These outcomes support the validity of the formative-formative type construct. The redundancy analysis to confirm convergent validity could not be performed, as global single items for the constructs were not considered in the questionnaire.

In the structural model, a conservatively significant ($p < 0.1$) path coefficient of 0.593 with a t-value of 7.95 is obtained by bootstrapping 5000 samples between INT and BEH. The predictive power of the structural model is assessed by the coefficient of determination, R^2_{adj} which is 0.342 with a t-value of 3.649, which suggests the significant extent of the model effect. Out of sample predictive power is assessed using the blindfolding method in SmartPLS 3. Using the blindfolding method, Q^2 of 22% is recorded for both BEH and INT, which depicts the medium predictive relevance of the model.

As shown in Fig. 4, the attitude of the farmers has the highest effect on whether or not they will retain or extend the width of VFS. They also perceive there exist some benefits of VFS that could improve the character of their field, which is evident by the PBC having a higher effect on intention (0.225). The farmers are not majorly influenced by the decision of their peers as it showed a non-significant effect on intention (0.05). From the extended constructs, it can be seen that farmers are more willing to have VFS on their fields if support is provided to them in the form of volunteers to help with the VFS, and if farmers can yield fruits from VFS. The impression of VFS being capable of generating cleaner runoff (overland flow) from their fields also makes it agreeable for the farmers to have VFS in their fields. The moral inclination to protect the environment for future generations and to maintain good water quality is also strong amongst the farmers as recorded by a high effect of BM on intention (0.214). Knowledge scored the least significant effect (0.198) on intention. It goes on to prove that depending on the task at hand, knowing does not always transcend into an intent to act. The loading of intention on behavior is 0.593, which identifies with the positive outlook farmers have towards VFS by the end of the survey.

3.2. VFSMOD-W modeling

Six different classes of fields are analyzed for four widths of VFS: 2, 5, 10, and 20 m. There exist natural buffers in the agricultural fields in the study area, which are not managed. This has been modeled in VFSMOD-W as an 'actual' case by using alfalfa as vegetation. The effect of VFS is simulated by using tall fescue as the VFS vegetation. Two cases 'actual' and 'VFS' are simulated to help the agents decide the comparison of soil losses. Simulations are performed for all the rainfall events during the period between 1998 and 2008.

As shown in Fig. 5, VFS of 20 m width performs consistently better compared to smaller widths. This indicates that opting for a VFS with larger width is the optimal solution to prevent soil losses in the agricultural fields. However, it should be noted that in ABM, the choice of width of VFS by agents is not solely dependent on retention efficiency.

VFSMOD-W is used in this study as a tool to obtain the difference in soil erosion and retention by a managed VFS and natural case only. The complete removal of VFS is not foreseen, as the conversion of riparian

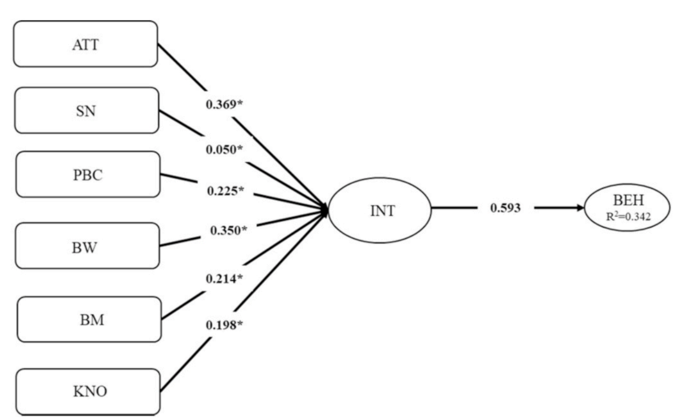

Fig. 4. Simplified higher-order formative-formative type PLS-SEM model of extended TPB results. *Total effects of extended repeated indicator approach.

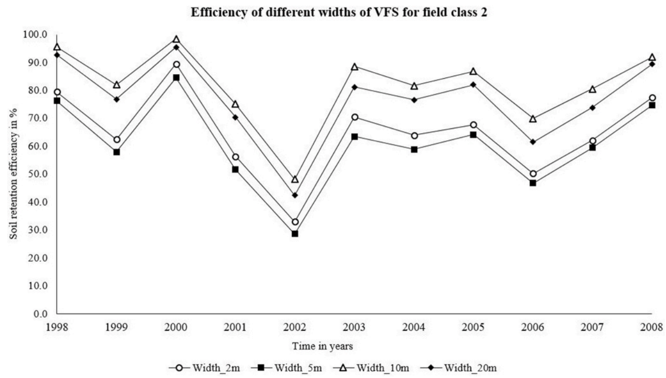

Fig. 5. Performance efficiency of different widths of VFS in soil retention for field class 2.

Table 4
Agent decision depending on the behavioral categorization.

Agent behavioral type	Width of VFS	1998	2000	2003	2006	2009
Perceptive	2 m	0	0	0	0	0
	5 m	1	0	0	0	0
	10 m	1	1	0	0	0
	20 m	2	3	4	4	4
Proactive	2 m	1	11	11	11	11
	5 m	5	0	0	0	0
	10 m	1	0	0	0	0
	20 m	4	0	0	0	0
Interactive	2 m	5	5	5	5	5
	5 m	19	19	19	19	19
	10 m	9	9	9	9	9
	20 m	16	16	16	16	16
Bounded rational	2 m	1	0	0	0	0
	5 m	2	1	0	0	0
	10 m	4	2	1	0	0
	20 m	3	7	9	10	10

land without VFS into managed or natural VFS is not. Such cases may be of interest in other studies with different land use characteristics. If a study is entirely dependent on a detailed design of VFS including vegetation, more sophisticated modeling with relevant sensitivity analysis; calibration and validation are recommended to be performed.

3.3. ABM modeling

The agents in ABM are assigned an initial buffer width same as the actual width reported by the farmers in the survey. Though it is evident from Fig. 5 that a larger width of VFS will reduce soil loss to a greater extent, it may not be the preferred choice of the farmers. This is because a larger width would imply loss of productive land and subsequently crop yield and income for the farmers. Farmers will also have to consider the annual maintenance cost that VFS would incur. Here, the behavioral classification and respective utility functions of farmers come into focus.

Based on the behavioral categorization and the utility function, the agents decide on the width of VFS once every 3 years as shown in Fig. 6. At the beginning of the simulation, 9% of the agents have a VFS width of 2 m, 37% of 5 m, 20% of 10 m and 33% of 20 m. By the end of the simulation period based on the utility generated over the years from the activities, 20% of agents opt to have VFS of 2 m width, 26% of 5 m, 12% of 10 m and 42% of 20 m.

Depending on the willingness to manage the VFS based on the different benefits, 40 (54%) farmers expressed strong agreement and 34 (46%) farmers showed a mild agreement to ‘don’t know’ in the onsite survey. In the developed ABM, by the end of the simulation period, 39 agents were convinced of the benefits of VFS and hence have opted for larger (10 m and 20 m) widths of VFS and those agents that showed milder agreement have chosen the smaller (2 m and 5 m) widths of VFS as seen in Table 4.

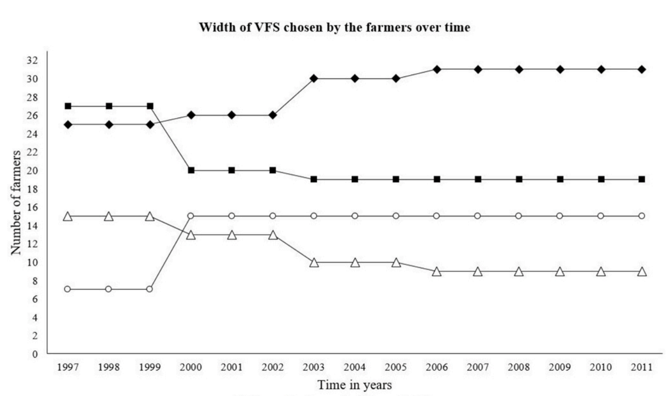

Fig. 6. Decision of the agents on the width of VFS at the end of every three years.

During the survey, perceptive farmers expressed their intention to have managed VFS in their agricultural field. They understand the long-term environmental benefits of having VFS in the region and their field. This can be seen in Table 4, which represents the change in the agents’ decisions with respect to behavioral categorization. The decision rule of perceptive agents allows them to increase the width of VFS unless they have a negative utility. It can be seen that as per their behavioral description, 2 of the perceptive agents have increased the width of VFS to 20 m by the end of the simulation period. A similar condition is observed from the bounded rational agents. These agents comprehend not only the utilities generated but also the short term and long term rewards of having larger widths of VFS. Since these agents perceive both monetary and environmental benefits, they gravitate towards larger widths of VFS.

We observe that the proactive agents adopt 2 m as their width of VFS by the end of the simulation period. Proactive farmers would try to maximize their profit and hence adopt the minimum possible option as simulated. The lesser the width of the VFS, the more active the field for agriculture is made available which increases their income. The decision rule for proactive agents lets them retain their initial width unless the current utility is less than the previous period’s utility upon increasing the width of VFS. Being profit-oriented is the characteristic choice of proactive agents.

Proactive farmers encourage interactive farmers to decrease the width of VFS while perceptive farmers encourage them to increase the width. Since the number of perceptive farmers in the study area is less, the proactive farmers sway the interactive farmers. However, it should be noted that interactive farmers are also subjected to the influence of bounded rational farmers. The number of bounded rational and proactive farmers is similar thus putting the interactive farmers in a state of limbo. Therefore, in ABM interactive agents have maintained their initial width until the end of the simulation period exhibiting no change. If bounded rational agents are well made aware of the environmental benefits of having wider VFS, they are also expected to increase the width of VFS as the combined effect of the subjective norm and morality is greater than perceived behavioral control.

The varying degrees of the area owned by the respondents along with their behavioral alignment has led the agents to not make a definite choice of a single VFS width which can also be witnessed in the real world. It must be noted that this study is modeled for the current generation of landowners and their current land-use practices only. This cannot be transferred to their offspring or the next generation as the behavioral orientation, market, economics could be completely different.

4. Conclusions

The results of VFSMOD-W show that having a managed VFS is more effective in retaining soil loss occurring in the agricultural field when compared to the natural case, which is the current situation of the farmers in the Larqui river basin, Chile. The larger width of VFS performs the best, which is evident from evaluating different VFS widths between 2 and 20 m. This study revealed that the farmers in the Larqui basin are not opposed to the idea of having a VFS as long as the utility generated stays positive. This has been proved from the developed interdisciplinary ABM and the on-site survey.

Farmer behavior whether individual or as a community is difficult and complex to capture. Patterns from the empirical data derived from a survey are used to form explicit assumptions about the behavioral categories of the farmers and behavioral observations from the real world with the backing of the theoretical perspective of TPB. ABM corroborates the complex network of understanding farmer behavior by TPB. It provides a great insight into the policies that could be developed in the future for the farmers to motivate them to prevent soil erosion using VFS as a sustainable approach. The understanding from this study could be further used to develop policies that motivate farmers to adopt sustainable agricultural and water management practices. The developed approach of combining the observed data, theoretical behavior model and agent-based modeling coupled with an environmental model can also be extended to other socio-hydrological or socio-environmental studies for developing tailor-made management policies.

However, it should be noted that economic, political and social dynamics affect the decision-making process. Re-creating the same response from the same set of the population at a different time duration would not yield the same results due to the changes in the economy, social awareness, and personal evolvement experienced by the respondents in the time between the two surveys (Öhlmer et al., 1998). In addition, human behavior is said to be non-predictable as it involves non-rational aspects as well. This makes it difficult to validate a specific ABM developed for a particular dataset with an alternative dataset. This can be partially overcome by introducing a relevant proven theoretical framework to ABM as in this study, which will improve the foundation of an integrated, complex quantitative framework, thus can make it more robust.

Additionally, the commitment to perform the behavior would lean out with time is not considered in this study. If the decision is to be made within a short time duration or if the implementation in itself has a short-term existential duration, then it has better chances of being attained compared to the long-term commitment. If the time given to decide is too much then a significant difference in the behavior can be observed. The temporal effect on the decision-making behavior of farmers can be analyzed in future studies. Anxiety to carry out a decision, tendency to not follow through will also affect the implementation of a behavioral intention in reality. This can be analyzed and reduced by the policy-makers by frequently interacting with the farmers and motivating them. Results of such efforts can also be evaluated in future studies.

One of the restrictions of such studies with a limited population is a relatively low statistical robustness due to the low sample size, which was overcome by using expert-based knowledge. Low sample size can be attributed to the combined aspects of geographical limitation, farmer population who had fields adjacent to the river and were dependent on the river, the willingness of farmers to participate in a survey, limited time to name a few. Since this paper addressed socio-hydrological aspects and not pure social science, an interdisciplinary attempt was done to develop a balanced combination of social scientific and natural scientific tools for modeling human-environmental feedbacks. The case study may serve as a proof of concept but not yet a general solution. In future studies, a large sample size collection to prove the statistical stability of the theoretical model should be ensured by choosing a study area with a large sample population. Furthermore, other fields of environmental management and other socio-economic conditions could be investigated.

Author contributions

Prajna Kasargodu Anebagilu: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review and editing, Software **Jörg Dietrich**: Conceptualization, Supervision, Writing - review and editing **Bruno Morales**: Software and Resources, Methodology **Lisette Prado Stuardo**: Investigation, Writing - review and editing **Jose Luis Arumi**: Supervision and Funding acquisition, Writing - review and editing **Etti Winter**: Supervision, Writing - review and editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112014.

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