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Integrated study and modelling of the factors affecting small-scale subsistence farming in eSwatini (southern Africa) through the use of causal diagrams and agent-based models

Prova finale in: Sistemi di gestione ambientale, di politica ed economia ambientale

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ABSTRACT

The dependence of small-scale subsistence farmers on natural resources has gained attention in recent decades highlighting the need of a transition to a more sustainable management of resources. An extensive literature is available on the structural factors affecting small-scale agricultural production in developing countries, while few studies are available on the role of social dynamics on the capacity of the system to react to adverse conditions. What are then the social, economic and environmental factors affecting small-scale subsistence agriculture? and, what is the effect of social behaviours on the adoption of agricultural innovation? This study is based on the specific case of eSwatini (southern Africa). A causal loop diagram was adopted to show the cause–effect relationship between variables. The role played by social behaviors in the diffusion of innovation is explored with the use of agent-based modelling (ABM). The model is based on agents, environment, links and five processes: crop production, social learning, individual learning, decision making, and resource recovery. In the simulation three farming behaviours can be adopted: no cropping, traditional practices or conservation agriculture (CA). The ABM was implemented in the Netlogo 6.2.0 platform. The case study is supported by scientific literature and interviews with local stakeholders. The results highlight the role of gender equality in the diffusion of knowledge. The model was run with and without gender equality for 10, 25 and 50 cycles representing farming seasons. The results show an increase in the spread of CA in the scenarios with no gender discrimination for which the rate of innovation adoption is faster. Moreover, the study casts light on the role of social learning and its dependence on training and education centres for the diffusion of new behaviours. Also, results show how an increase in the number of learning centres leads to a higher rate of knowledge diffusion.

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0. INTRODUCTION

Worldwide natural resources are depleting at an alarming rate (Food and Agriculture Organization of the United Nations, 2017). This is owed to a number of factors which cannot be summed up into one entity. The current production and market system is leading humanity to worrying levels of environmental degradation and depletion of natural resources. The growing population of the planet continues to withdraw resources, water and energy from the environment, to spread pollutants and disperse waste, causing damage to the territory, air and water in some cases irreversible. The world population is expected to grow by over a third, or 2.3 billion people, between 2009 and 2050. Nearly all of this growth is forecast to take place in the developing countries (Food and Agriculture Organization of the United Nations, 2017). A growing population leads to a higher demand for agricultural products which puts natural resources – land, water and biodiversity – under increasing pressure. Agriculture in the 21st century faces multiple challenges: it has to produce more food and fibre to feed a growing population with a smaller rural labour force due to the urbanisation process, contribute to overall development in the many agriculture-dependent developing countries, adopt more efficient and sustainable production methods and adapt to climate change (Food and Agriculture Organization of the United Nations, 2017) which make the sector a key component for growth and development at a global level.

This is particularly true in the case of developing countries where the agricultural sector is at the heart of the economies. In these areas, agriculture accounts for a large share of gross domestic product (GDP) (ranging from 30 to 60 percent in about two thirds of them), employs a large proportion of the labour force (from 40 percent to as much as 90 percent in most cases), represents a major source of foreign exchange (from 25 percent to as much as 95 percent in three quarters of the countries), supplies the bulk of basic food and provides subsistence and other income to more than half of the populations. Thus, significant progress in promoting economic growth, reducing poverty and enhancing food security cannot be achieved in most of these countries without developing more fully the potential human and productive capacity of the agricultural sector and enhancing its contribution to overall economic and social development (FAO, 2002). Small-farmers in developing countries, make up to 70-95% of the farming population and traditionally survive on subsistence production (Kwa, 2001). Subsistence farmers are those farmers that produce crops and raise livestock on a small piece of land while using available resources which exclude expensive modern technology and machinery (Rugube et al., 2019). The literature on smallholder farmers throughout developing countries reports that they reside in remote rural areas with underdeveloped infrastructure, they are poor, lack assets, cannot access finance, have small land parcels usually with low fertility, low levels of education, poorly coordinated value chains, and are elderly (Simelane et al., 2019) the combination of this factors results in low yield productivity at the farm level. The contribution of subsistence farming to food security issues in developing countries has been widely reported in literature and highlights its role in reducing vulnerability, improving livelihoods, and helping to mitigate high food price inflation (Baiphethi & Jacobs, 2009). These findings highlighted the need to significantly increase the productivity of subsistence/smallholder agriculture to ensure long-term food security both at the rural and urban level. This can be achieved by encouraging farmers to pursue sustainable intensification of production through the use of improved technologies and practices (Baiphethi & Jacobs, 2009). One of the major discussions related to small scale production concerns the need of a transition to the adoption of climate resilient practices which lead to a sustainable management of natural resources and input, reducing farm dependence on scarce resources and decreasing land and water degradation.

Communities in low and middle-income countries in fact, are heavily dependent on natural resources for their livelihoods, which makes them especially vulnerable to the impacts of climate change (Parry, 2007). The effect of climate change is accelerating environmental changes such that farmers will need to observe, learn, and respond more quickly than before requiring new means of sharing information in order to tackle with increasing uncertainty and low adaptation means. This approach comes with many challenges that necessitates technological innovation and farmer adaptation (Mlenga & Maseko, 2015). This ability to adapt can be improved in farms through internal and external interventions, enhancing farmers capacity to self-organize and adopt innovative problem-solving. Previous studies investigated the adoption of innovative agricultural practices among farmers and beside physical and economic limitations, the findings highlighted the role of psychological factors influence on farmers adoption of adaptation strategies (Kangogo et al., 2020). A study conducted in Kenya identified farmers innovativeness, educational level, access to credit and membership in community organization, among others as significant determinants of the adoption of climate resilient practices in the country (Kangogo et al., 2020). In eSwatini, previous studies found a significant association between technology adoption, age, farming experience, training received, socioeconomic status, cropping intensity, aspiration, economic motivation, innovativeness, source of information and agent’s behaviour (Mlenga & Maseko, 2015). Other studies state that due to resource limitations and gender discrimination in extension message delivery, female farmers are less likely to adopt CA technologies in eSwatini (Mlenga & Maseko, 2015). With respect to farmers' motivations and barriers to the adoption of sustainable agricultural practices, a rich body of literature is available. However, a knowledge gap persists in understanding how farmers consciously adapt their farming practices to face food requirements in harsh changing (environmental) conditions. The importance of filling this gap comes to support farms in the transition to more suitable practices in order to face unpredictable environmental variations through the adoption of improved environmental resources management while reducing farm dependence on their scarce availability. Adaptation in this context, intended as the adoption of 'best' agricultural practices to face uncertainty, is therefore linked to the identification of cultural and traditional factors which affect the spread of knowledge and the learning process in the network and limit the diffusion of innovation as a result of social interactions in the community (e.g., gender discrimination) which affect individual's actions and influence its capacity to evaluate risk and adaptation, affecting their final decision in adopting new agricultural practices.

0.1 Goal of the study

This MSc Thesis work aims at identifying the social, economic and environmental factors influencing small-scale subsistence agricultural production in eSwatini (southern Africa). The study aims at investigating what are the social, economic and environmental factors affecting small-scale subsistence agricultural production in eSwatini and the effect of social behaviours on the adoption of agricultural innovation among small scale subsistence farmers. Two modelling methodologies are used to investigate the gap: a causal loop diagram (CLD) (Forrester, 1999) was implemented in the Vensim PLE platform and used for the investigation of the cause–effect relationships and the definition of the qualitative variables in the system's structure which affect small-scale production capacity. The CLD was used for the exploration of the complex social and economic structure of the system allowing for a macro-level analysis of the agricultural system in the country. The CLD laid the theoretical foundations for the construction of the agent-based modelling (ABM). The micro-level of the system is taken into analysis and refers to the role played by traditional laws and social behaviours in the diffusion and adoption of innovative agricultural practices in eSwatini rural communities and is explored with the use of ABM, which provides a viable scientific approach for representing human decision-making processes (Balke & Gilbert, 2014) and complex interactions between humans and their environments. The agent-based model was implemented in the Netlogo 6.2.0 platform (Tisue & Wilensky, 2004) and is built as a social space on the basis of Social Learning Theories introduced by the psychologist Albert Bandura (1977) in which agents learn and behave according to social interactions and individual perceptions of the outcome. In the simulation three agricultural behaviours can be adopted by the farmer: no cropping, traditional agriculture and conservation agriculture. Environmental assumptions concerning each agricultural practice in the study are based on literature and are evaluated by agents during the simulation in order to represent the issues related to resources consumption for each practice, while no economic considerations have been implemented in the ABM. This decision is driven by the will of focusing first on the non-economic factors since agent's behaviour is assumed not to be based on rational economic decisions. Human interactions are strongly driven by non-rational factors (e.g. status/power relations) which affect the overall output of the system. The model outcome is explored using Sensitivity Analysis (Broeke et al., 2016) in order to investigate the effects of the Social Learning Theory on the decisional process of farmers and on the overall system's capacity to face uncertainty and innovation.

1 CASE STUDY AND METHODOLOGY

1.1 Case study

1.1.1 The Kingdom of eSwatini

The Kingdom of eSwatini is the smallest country in southern Africa, and lies between latitudes 25°43’ and 27°19’ S and longitudes 30°47’ and 32°08’ E covering a surface area of 17,364 km2 and has approximately 12 220 km2 of agricultural land, or 71% of the total land area (FAO 2013) (Figure 1). According to the 2019 census, the population is estimated at 1,093,238 persons with an annual growth rate of 1.0% (World Bank 2020). The country borders the Republic of South Africa in the north, west, and south and Mozambique in the east. For administrative purposes the country is divided into four districts (Hhohho, Manzini, Lubombo and Shiselweni) and is classified into four agro-ecological zones (AEZ): Highveld, Middleveld, Lowveld and Lubombo (Figure 2). Elevation, landforms, geology, soils, climate and vegetation of the four AEZ are reported in Table 1. The government is an absolute monarchy, ruled by King Mswati III since 1986. With a GDP per capita of $3,762 in 2021 (World Bank Group, 2020), it is classified as a country with a lower-middle income

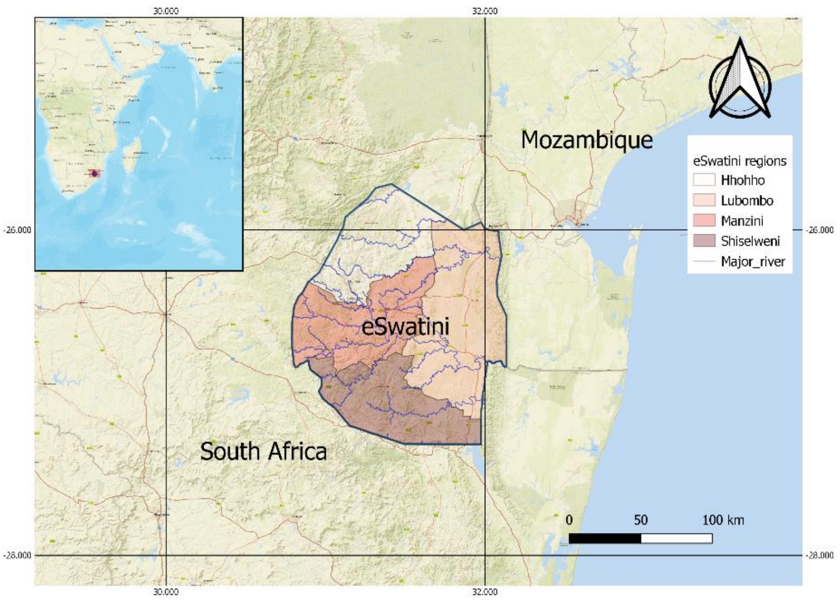

Figure 1 Map of eSwatini

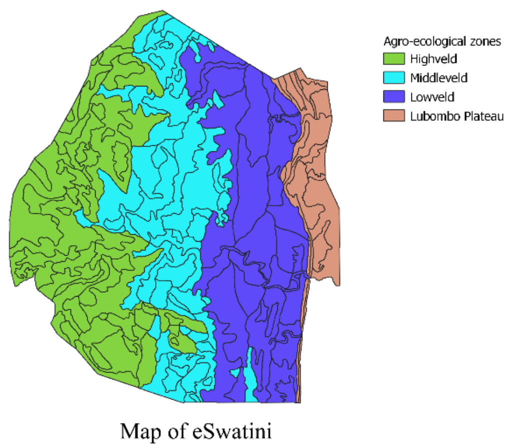

Figure 2 eSwatini agro-ecological zones (AEZ) by the International Monetary Fund. Although income inequality is relatively high in the country resulting in a Gini Index[1] of 0.49 in 2017 (World Bank Group, 2020).

1.1.2 Climate

The general climatic characterisation of the Kingdom of Eswatini is subtropical, with wet hot summers from October to March and cold dry winters from April to September. The physiographic zones clearly show different climatic conditions, ranging from sub-humid and temperate in the Highveld to semi-arid and warm in the Lowveld. The long-term average rainfall figure for the Highveld, the Middleveld, the Lowveld, and the Lubombo Plateau are 950 mm, 700 mm, 475 mm, and 700 mm respectively. Average maximum and minimum monthly temperatures are 22 °C and 11 °C in the Highveld and 29 °C and 15 °C in the Lowveld. The national long-term average rainfall is 788 mm per year. According to (Tfwala et al., 2020) droughts have increased in prevalence and severity after the year 2000, especially in the dry Lowveld. The frequency of droughts is higher in the dry areas of the country compared to the high rainfall areas. The author highlighted droughts are generally increasing in the country.

1.1.3 The agricultural sector

After gaining independence in 1968 from the British Empire, the Kingdom of Eswatini experienced diversified economic growth that focused on agricultural growth in sugarcane, maize, and cotton, and pursued policies that pushed towards foreign and private investments. The agricultural sector in Eswatini is one of the crucial sectors for the economy since it provides the raw material that is used by the other sectors and it contributes about 8,7% to the country's Gross Domestic Product (GDP) with the third highest percentage to the economy after service (52%) and manufacturing (36%) sectors (World Bank Group, 2020). The agricultural sector is the backbone of the country's economy and is also a major source of income, employment and food for rural people with over 70% of the population fully dependent on this sector for livelihood (FAO, 2015a). Agriculture in eSwatini is split between largely rain-fed subsistence production by smallholder farmers in SNL (Swazi National Lands), which are royal lands distributed to the population by local chiefs according to traditional practices, that grow rain-fed maize and vegetables representing 90% of total smallholders; and Title Deed Lands (TDL), cash cropping with available irrigation on large private estates (Worldbank, 2011). The sector is predominantly constituted by smallholder farmers on Swazi National Land (FAO,

1 The Gini index measures the extent to which the distribution of income among individuals or households within an economy deviates from a perfectly equal distribution (World Bank Group 2020).

2018) dependent on the rural economy, which is dependent on rain-fed agriculture. Although smallholder producers constitute 70% of the population and occupy 75% of the crop land, yet contribute only 11% of total agricultural outputs in the country, with average cereal yields as low as 1.1 tonne/hectare (eSwatini, 2018a).

Table 1 Source: Internationl Monetary Fund 2004. Note: Figures do not tally exactly with GoS statistics (GoS & FAO, 2005)

Agroecological Zone Altitude & % of total land area	Dominant Landform and Geology	Inherent Vegetation	Land Degradation
Highveld 900–1400m 33%	Dissected escarpment, basins and plateaux (Granite)	Short grassland with forest patches	30% serious erosion 40% poor range conditions
Upper Middleveld 600–800m 14%	Medium & low hills, basins & plateau remnants (Granodiorite/Granite)	Tall grassland with scattered trees & shrubs	50% serious erosion 70% poor range conditions
Lower Middleveld 400–600m 14%	Rolling plain with low hills (Gneiss)	Broad leaved savanna	20% serious erosion 25% poor range conditions
Western Lowveld 250–400m 20%	Undulating plain (Sandstone/Claystone)	Mixed savanna	10% serious erosion 60% poor range conditions
Eastern Lowveld 200–300m 11%	Gently undulating plain (Basalt)	Acacia savanna	5% serious erosion 40% poor range conditions
Lubombo Range 250–600m 8%	Undulating and dissected cuesta plateau (Ignimbrite)	Hillside bush and plateau savanna	5% serious erosion 5% poor range conditions

1.1.4 Land tenure and land use

The two land tenure forms are Tittle Deed Land (TDL) and Swazi Nation Land (SNL). TDL comprises around 25% of the land while SNL accounts for 75% of the land and is held in trust by the King for the Swazi Nation (Manyatsi & Singwane, 2019)(Figure 3). Production on SNL is primarily subsistence rain-fed agriculture. Farmer’s objective under a subsistence system is mainly food security and is achieved through own production of inputs such as retained seed (L. N. Dlamini, 2019). Maize is the primary subsistence crop in eSwatini (Kunene, 2019), often used as an indicator of food availability in the country (FAO 2005). Maize is quite frequently mix-cropped with cucurbits, legumes, sweet potatoes, and sorghum. Farming techniques on SNL are almost exclusively traditional, using very simple tools and employing predominantly family labour and draught animals. In recent years, as a result of the development of rural irrigation schemes with the aim of stimulate the production of market goods, farmers have increased production of some **cash crops on SNL**, such as sugar, cotton, tobacco, and vegetables, but this still represents a small proportion of the total SNL agricultural production and often generates disputes regarding the price offered for their purchase by the processing companies (Masuku, 2011). TDLs produce for the market. The crown land is allocated to individuals or companies who intend to make developments that would benefit the public. The benefits could be in the form of employment opportunities brought about by investments. Titled land contributes about 60 per cent of the total agricultural output, accounts for a sizeable proportion of total merchandise exports and provides the basis for most of the manufacturing activity in the country. For this reason, the benefits of agricultural production are skewed in favour of a small minority, the majority of which are foreigners. The TDLs are predominantly cropland, livestock ranches, timber and fruit plantations, and mining concessions. Production techniques on most of the TDLs are modern and intensive, including use of full inputs and mechanization. The bulk of output produced in this subsector is intended for the market, both domestic and foreign. Sugar and timber are the principal commodities and account for a sizeable proportion of total merchandise exports. About 60 per cent of the national agricultural production originates from the TDLs, and includes other important commercial crops such as cotton, citrus, pineapples, tobacco, and livestock.

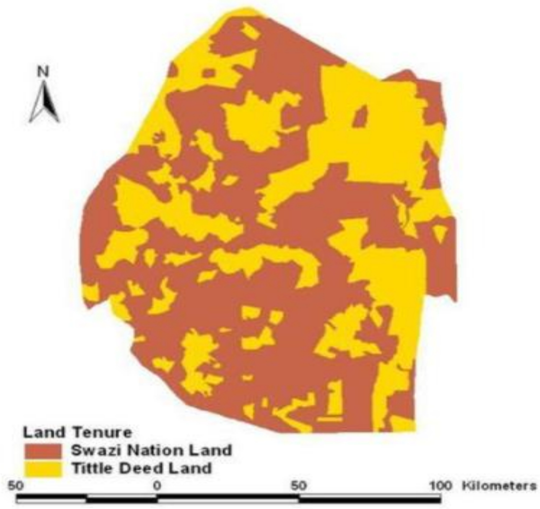

Figure 3 Land distribution in eSwatini: public land (SNL) vs private estates (TDL) (Manyatsi & Singwane, 2019)

1.1.5 Land policy and traditional structure

The Constitution of Eswatini (2005) recognises the rights for all individuals to own property, including land. However, the majority of the population do not have the financial resources to own it, and they occupy SNL where they cannot own the land, but have the right to use it until defined by the local Chief (e.g. expropriation for public use or eviction). The allocation of communal land (SNL) follows Swazi customary law, where a tribal chief allocates land to household heads of his subjects through *kukhonta* (paying allegiance to the chief). There is no written evidence of the farmers' rights to use SNL since public land has no inventory and valuation at governmental level and often boundaries between chiefdoms are not adequately defined, causing disputes and eventually eviction of the dweller. The absence of a **Land Policy** concerning SNL is identified as a key constraint to the reorientation of agricultural production systems to enable small farmers to create wealth for themselves, thereby making a significant and positive contribution to food security, rural development, employment creation and poverty reduction in Swaziland (Manyatsi & Singwane, 2019). One of the major constraints regarding land is that currently SNL cannot be used as collateral for sourcing **financial credit** on banks (Manyatsi & Singwane, 2019). Limited household rights to Swazi Nation Land (SNL) affect crop production since capital is essential for providing improvements in land and purchasing farm inputs (L. N. Dlamini, 2019). Moreover, the occurrence of discrimination in land allocation is still a common issue in the country, in fact, as a result of the recognition of women's role in the agricultural sector the Constitution has introduced allocation of SNL to women regardless of marital status and permits women to register private property in their names, although the laws dealing with property rights have not been aligned with the requirements of the Constitution and despite having a prominent role in the food system, customary practices restrict women access to the land, agricultural extension services, credit, infrastructure, technology and markets that are crucial to enhancing productivity and livelihoods at household and community level (L. N. Dlamini, 2019).

1.1.6 Environmental resources, rural development and food insecurity

Smallholder producers constitute 70% of the population and occupy 75% of the crop land, yet contribute a meagre 11% of total agricultural outputs in the country, with average cereal yields as low as 1.1 tonne/hectare which makes eSwatini a food deficit country (eSwatini, 2018a). SNL farmers are faced with a variety of problems resulting in poor performance. According to (Mlenga & Maseko, 2015) sub-Saharan Africa farming is characterized by poor soil fertility, low rainfall distribution and low levels of agricultural technology use. This combined to the effects of climate change, which result in high precipitation variability and higher draughts frequency in various areas of the country (Tfwala et al., 2020), represent a major thread for agricultural production, negatively affecting agricultural yields, biodiversity, forests and the availability of clean water in the area (eSwatini, 2016b). As a result of the poor performance of the agricultural sector and the need of supporting small-scale producers in facing changing environmental conditions, the Ministry of Agriculture (MOA) in collaboration with the Food and Agricultural Organisation of the United Nations (FAO) and the

Cooperation of the Development of Emerging Countries (COSPE) since 2002 has extensively promoted the adoption of conservation agricultural practices (CA), due to the globally observed benefits linked to its adoption that include sustainable land use, increased yields, increased incomes, timeliness of cropping practices, ease of farming and ecosystem services (Mlenga & Maseko, 2015). Conservation agriculture amongst other agriculture technologies has been acclaimed as a practice that will enhance sustainable and intensified agricultural production (FAO, 2008). CA in fact, has been promoted to maintain and improve yields and resilience against drought and other hazards while at the same time stimulating biological functioning of the soil practices such as direct sowing, zero-tillage or minimum tillage, moreover, the establishment of cover crops help to protect organic matter and soil fertility (Mlenga D. H., 2015). Although, despite its global success, the adoption of CA in Africa including eSwatini, is still relatively low (Nyanga, 2012) and according to (Mlenga & Maseko, 2015) this represents one of the causes of low agricultural performance in the country.

In this framework, poor production methods add to the adverse socio-economic context encountered by small farmers in rural areas, which affects their capacity to access innovation and materials. These include poor infrastructure development such as inferior communication networks, undeveloped feeder roads, absence of irrigation schemes and inadequate marketing facilities, resulting in low-quality products and limited quantities. MOA (Ministry Of Agriculture) extension services which role would be to support farmers in agricultural development and welfare increase are no longer effective in various areas. Extension Officers are often low qualified, provide inconsistent technical advice to farmers since are not equipped to provide up-to-date information about existing technologies, and do not have the capacity to involve farmers in adaptive trials of promising new technologies (Worldbank, 2011). In eSwatini, maize is used as measure of food security (FAO, 2005). The country is a net importer of maize and satisfies its supply deficit almost entirely with maize grain from South Africa. Maize is the staple food crop grown on Swazi Nation Land for subsistence purposes and food security (eSwatini, 2016b). However, though a substantial number of rural households produce it, the country has never produced enough for total domestic consumption, eSwatini in fact, only produces enough to meet about 45% of its annual total cereal requirements (Sacolo et al., 2018). The dependence of the country on **food imports** affects food security at the national level adding to the causes that limit the **access of small farmers to food markets**. Indeed, the effects of the continued increase in imports and slump in local production make the country more exposed to global developments in markets. Price volatility in a stable food like maize is particularly important for eSwatini in that most emaSwati[2] are poor and it is known that poor segments of society

[2] eSwatini population

spend most of their income on food (Sukati, 2013). This means that unpredictable spikes in stable food prices that form major caloric intake become an important food security issue. Adding to this, the effect of unpredictable weather patterns and climate change in the area result in unpredictable price movements in agricultural commodities by causing supply disruptions (Sukati, 2013) with effects on accessibility to food by the vulnerable and poor due to their low purchasing power (Sacolo et al., 2018). On the other side small farmers in eSwatini, and especially smallholders, face enormous challenges finding markets for commercialisation. Local markets are frequently flooded with low-price products from foreign countries, and local Institutions that have been established to support farmers in the marketing of their produce, such as the National Agriculture Marketing Board (NAMBoard), the National Maize Corporation (NMC), the Swaziland Dairy Development Board (SDDB), and the Swaziland Cotton Board (SCB), reach relatively limited numbers of clients. Moreover, the high cost of farm inputs such as seeds, fertilizer and hiring tractors for farm operations, which are provided by private companies related to parent companies in South Africa, is compounded for poorer farmers by the lack of access to short-term production credit and affects **farmers competitiveness on market prices.** This reduces their incentive to participate in economic transactions and result in subsistence rather than **market-oriented production systems** (Xaba & Masuku, 2012).

Unreliable agricultural productivity coupled with escalating poverty levels in rural areas led some households to diversify their portfolio of income sources, with those from outside agriculture representing the majority. Households' access to food is dependent on the occupation status since a large proportion of the food consumed is purchased (Mabaso et al., 2020). Although forms of wage employment opportunities available in the rural areas are non-specialized and low remunerated (Mabuza et al., 2016) providing low and discontinuous means to face food insecurity.

1.2 Modelling methodologies

Two modelling methodologies have been used in this study for the investigation of the structural and social factors affecting small scale production in eSwatini. The System Thinking approach was adopted for the identification of the cause-effect relationships among variables: a causal loop diagram (CLD) was created in order to identify and map the economic, social and environmental factors which affect the agricultural capacity of small holder farmers in the country. On the other side, the effect of social behaviors and traditional laws was explored through the use of agent-based modelling (ABM), which allowed for the investigation of the role of social dynamics in the transition to new agricultural behaviors.

1.3 Data for the models

The models are based on various types of data sources: scientific literature was investigated to identify the environmental, structural and cultural components and constrains of the system. Assumptions related to both cultural and structural factors were verified through interviews with local stakeholders (COSPE NGO), following an internship collaboration with the organization which took place in 2020. Data were expected to be in part directly collected although eventually this was not possible due to the Covid-19 Emergency.

1.4 The System Thinking approach

Complex systems are composed of various parts interacting between each other. From these relationships distinct properties arise, such as nonlinearity, emergence, spontaneous order, adaptation, and feedback loops, among others. The System Thinking approach has been evolving and developing over the last 60 years and is increasingly having more influence on science (Haraldsson, 2004). It is a method of making sense of a system of components and how these components relate to each other, allowing for the investigation and the representation of complex, dynamic systems while demonstrating how they behave over time. The systems thinking embeds two other concepts, System Analysis (SA) and System Dynamics (SD) which provide insights into the structure and behavioural patterns helping to reveal the root causes of challenges, plan the future, reduce risk, anticipate delays and prevent unintended consequences (Banson et al., 2015). In general terms system thinking is the mental modelling and science of structuring the logic and asking the relevant questions, but it also has practical applications through System Analysis and System Dynamics (Figure 4).

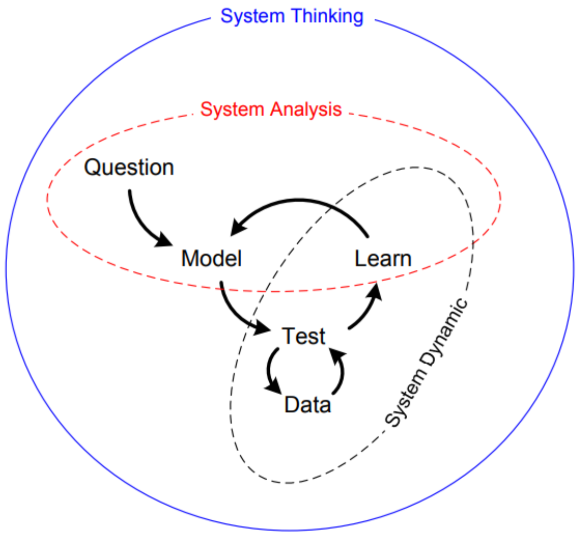

Figure 4 Systemic Thinking allows for the investigation into system's property and functions, involving a mental model of the problem (Systems Analysis) and a mathematical representation (System Dynamics) (Haraldsson, 2004)

System Analysis (SA) is about discovering organisational structures in the system and creating insights into the organisation of causalities. It allows for the understanding of the components and feedback relationships. The structure of the complex system is captured through the use of diagramming tools, such as causal loop diagrams (CLDs) for the qualitative overview of the variables affecting the output and represents the mental model of the problem. System Dynamics (SD) was first created by J. W. Forrester at Massachusetts Institute of Technology (MIT) in 1950. SD refers to the re-creation of the understanding of a system and its feedbacks with the use of a top–down information feedback method which provides a well-developed approach for visualizing, analysing, and understanding complex dynamic feedbacks. The modelling allows to explain the past and predict the future. Furthermore, System Dynamics deals with mathematical representation of the mental models (SA) and is a secondary step after its development. Various authors highlight the importance to deal with agricultural challenges with a new systemic approach to determining interventions (e.g., policy making and enforcement) and capacity building to enhance a new, more holistic way of thinking to evolve, improve and raise the efficacy of the agricultural industry (Banson et al., 2015). The address of problems in integrated approaches with systems thinking models demonstrates how to translate ideas into management tools for change (Nguyen & Bosch, 2014; Sherwood, 2011) rather than adopting traditional reductionist approaches which often provide quick solutions that treat the symptoms of the problem and result in unintended consequences due to the partial consideration of the involved system (Banson et al., 2015). In this study the basic principles of the system thinking methodology are applied: the structure of the complex agricultural system is captured through the use of a CLD for the qualitative overview of the social economic and environmental variables affecting the system, allowing for the investigation of the cause-effect relationships affecting small scale production in the country. The methodology of research used for the model development includes literature and stakeholder's interviews. The combination of data obtained from eSwatini, interviews and the literature review gave an overview of the current structure and management strategies on the agriculture system riddled with feedback loops. The modelling into a systems structure was realized using the VENSIM software program. In the current model no mathematical implementation was developed due to the aim of the study of representing an integrated approach for the investigation of the systems' complexity rather than representing analytical data concerning each variable.

1.4.1 Structure of a Causal Loop Diagrams

Causal loop diagrams (CLDs) are able to map the structures of a complex system in order to understand its feedback mechanisms; they can show how the system is dynamically influenced by the interactions of all of the variables. CLDs describe the reality through causalities between variables and how they form a dynamic circular influence, allowing to observe the world through feedbacks rather than linearly (*Figure 5*) allows the understanding of causes and effects. The structure of a CLD consists of variables connected by arrows; the arrows denote the causal influences among the variables. Each causal link is assigned a polarity—either positive (+) or negative (−)—to indicate how the dependent variables are influenced by the independent variables (causal linkages) (Ding et al., 2018) and eventually the cause-effect relationships are assigned with a 'delay' symbol for the identification of those processes which affect the system at different timesteps. Feedback loops in a CLD indicate feedback in the system being represented. This indicates that a given change kicks off a set of changes that cascade through other factors, ultimately leading back to a previous variable creating a feedback loop. A feedback loop can be either reinforcing (R), if events or behaviours created by the variables in the loop amplify each other, leading to unbounded growth or decline, or balancing (B), if some variables create counteracting changes, resulting in equilibrium. An easy way of assessing the effect of the feedback loop is to count the number of negative signs in the loop; an even number results in a reinforcing loop, and an odd number results in a balancing loop (Kirkwood 1998) so as to either amplify ('reinforce') or push back against ('balance') the original change. *Figure 6* and *Figure 7* provide an explanation of the symbology used in the diagrams (Haraldsson, 2004).

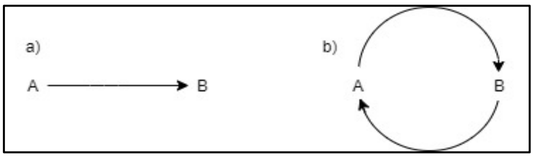

Figure 5 a) linear representation of causal links; b) circular representation of connection between variables.

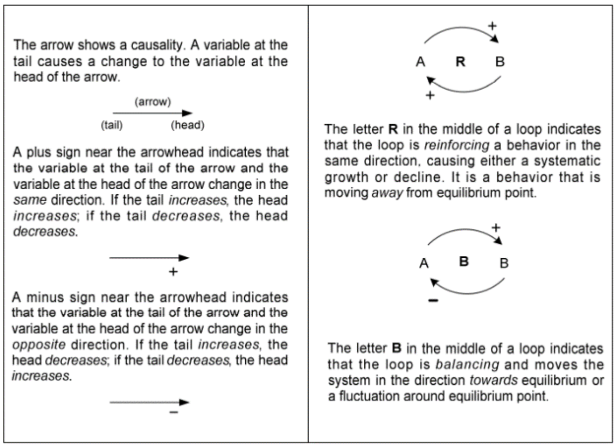

Figure 6 Causal Loop symbols explained (adopted from Roberts et al. 1983, p56)

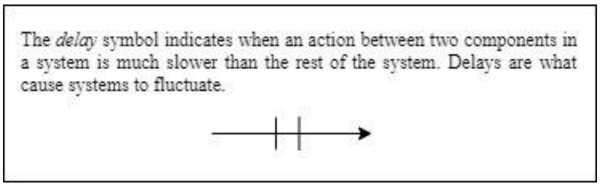

Figure 7 Delay representation in CLDs (Haraldsson, 2004)

1.4.2 Building the Causal Loop Diagram

The building of the CLD started by the identification of the structure of the system, its barriers to success and the system drivers in relation to the key outcome investigated, this was made through in-depth literature study (Table 2) and focus discussions with a group of experts from COSPE Ngo who act locally for the development of small-scale producers. The definition of the variables is defined in this phase starting from the key outcome investigated and then working backwards, adding enabling or dis-enabling variables, until the reach of the limits of the system of interest. For each variable both consequences and additional causal influences are considered. In the final step, the model is investigated and explored for the identification of patterns in their interconnected components and by analysing the reinforcing and balancing feedback loops. Assumptions concerning the leverage points of the system are presented in the discussion. Leverage points are places within a complex system where a small shift can generate a bigger change in the whole system which can lead to significant lasting improvements (Banson et al., 2015).

Table 2 Keywords at the base of the literature research for the CLD

Keywords	Subsistence farming; livelihoods; agro-food markets; farm inputs; food security; agricultural finance; climate changes; land tenure; land governance; rural development; irrigation; rural infrastructure; cash crop; agricultural investment; import; subsidies; production input; information; training; education.

1.5 Agent Based Models

Agent-Based Modelling (ABM) is a natural way of representing socio-cognitive behaviour of individuals and simulating complex interactions between individuals and their environment (Berger & Troost, 2014; Cioffi et al., 2015). It provides a viable scientific approach for representing human decision-making processes (Balke & Gilbert, 2014) and complex interactions between humans and their environments (both natural and artificial) at different spatial and temporal scales (Heppenstall et al., 2012). Agent based modelling provides a dynamic approach by building a virtual system. The model follows a "bottom–up" procedure that emphasizes the spatial or social interactions between individuals and their environment. The methodology is an effective cross-scale modelling method that can be used to explicitly describe organizational scales, such as different networks, and bears the characteristics of heterogeneity, space discretization, time discretization, and discrete states. Through computer simulation, the microscopic mechanism of complex macro phenomena can be revealed, allowing for developing an understanding of the complex adaptive system under investigation, where assumptions about processes and interactions can be explored through simulations. Such models can also be used as computational laboratories for exploring scenarios that focus on people's local adaptive responses to different socio-economic factors and the effects on their ecosystems. Accordingly, several agent-based models have been developed to examine interactions between rural household and their environment (Cioffi et al., 2015). Although previous models provide many insights on the impact of human actions on the environment and vice versa, they either exclude the representation of socio-cognitive behaviour of households and their network or greatly simplify the adaptive behaviour and responses of households to climate changes (Crooks, 2018). In this study an Agent Based Model (ABM) was developed in order to explicitly include rules of social behaviour and decision-making of agents, the interaction network of agents, and the diversity within the agent population(s) and changes therein. We consider the specific agricultural systems of eSwatini (southern Africa), although since the intention is to investigate the effect of Social Learning Theories on the systems dynamics, little attention is given to specific environmental and economic elements which have been assumed or are not considered in the modelling. A specific agricultural system is considered, i.e., the model includes features shown by the specific reality of eSwatini, although various similarities to production systems in other developing countries have been identified. Note, that in the current model system dynamics (like crop growth and weather processes) have been excluded for simplicity. There is no biophysical or economic theory involved in the model; instead, the ABM is focused on the inclusion of factors representing non-economic behaviour, in particular social learning. The agents' motive is driven by physiological needs and safety needs to maximize their production following Maslow's hierarchy of needs (*American Psychological Association (APA)*, 2021). Maslow identifies physiological survival as farmers primary need followed by the need of safety which in the model relates to agricultural production safety, measured by agents though an evaluation of yield production over time which affects individual's perception of good or bad outcomes and drives individual's decision making concerning the adoption of a behavior. Social relations in the model are constituted wholly by the power and status dimensions (Kemper, 2006). Power-Status theory holds that when human actors orient their behaviour to each other, two fundamental dimensions, namely power and status, are operative. Power in the model is represented by the pressure performed by traditional authorities over the agents in terms of access to community resources (land) and services (training) and is representative of gender discrimination in eSwatini rural realities. According to (Kemper, 2006) an actor with high status is one who receives benefits and rewards from the other actor(s) in the relationship. In the model status is linked to the level of education acquired by agents during the simulation combined with the amount of crop produced with effects on the social learning process for which agents will observe others behaviours in the network and evaluate the adoption of those with higher status. The model testing was performed by peer review by a MSc student involved in the Resilience Team at WUR; One Factor at a Time (OFAT) Sensitivity analysis was conducted to extract relations that may be used in validation of the model. The full model description and ODD (Grimm et al., 2013) can be found in Appendix 2. In the next section a summary of the model description, flowchart, and decision making are provided.

1.5.1 Theoretical Models of Decision Making and Social Learning

The role of ABM in the study is to identify and model the effect of individual and social factors which have a major influence on individuals' decisional process in order to include relevant communication considerations. The model is based on the theoretical framework of the Social Learning Theory which defines human behavior as a triadic, dynamic, and reciprocal interaction of personal factors, behavior, and the environment. The architecture for the general model shown in *Figure 8* is a simplified version of the full framework, which draws on past literature and focuses on social and psychological factors (Nowak et al., 2017). In the ABM model, the "propensity" to engage in a particular behavior, incorporates beliefs, norms, self-efficacy, and intention, as well as other external factors such as access and barriers. This *propensity* determines the intention with which the individual makes a particular decision, and behaves accordingly, then, he or she will experience an outcome as a result of that behavior.

The individual's experience can be relayed to others in the social network, which influences are described as "Observed information" in *Figure 8Figure 8*. Coupled social network information about behavior and outcomes can influence others' beliefs about the behavior.

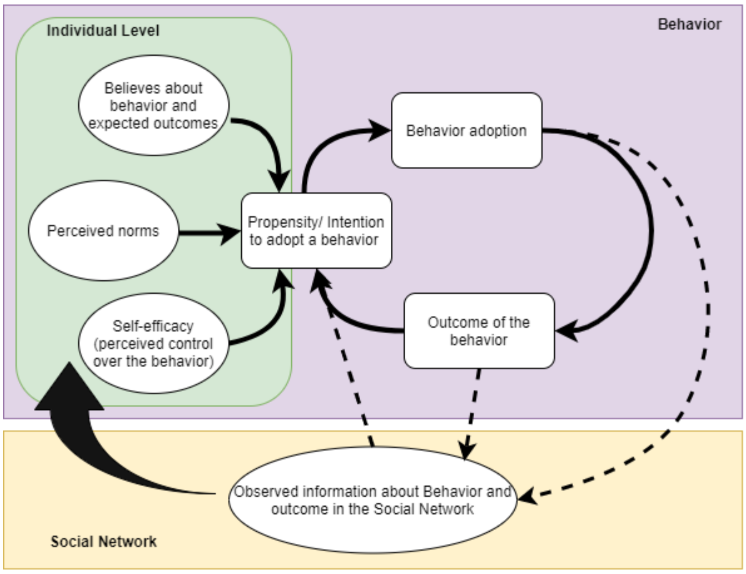

Figure 8 Simplified framework of Social Learning mechanisms in modelling. Inspired and substantially modified from Nowak et. al., 2017

1.5.2 Model design

The model was inspired by (Baggio & Hillis, 2018) and (Chen, 2018). The model was developed with three elements (agents, environment, and links) and five processes (crop production, social learning, individual learning, decision making, and recovery) as shown in *Figure 9*a. During the simulation agents perform social behaviours which dynamics are shown in *Figure 9*b representing an in-depth of the mechanisms affecting agent's Learning process and decision-making when evaluating the adoption of new practices. At the start of each agricultural season (1 tick in the NetLogo program), a sequence of activities takes place in the order as follows. At the beginning of the run consumed resources for crop production are subtracted from available natural resources on each patch depending on the practice adopted by the agent in the previous run. Next, agents involve in the learning process and decision-making mechanisms (*Figure 9*b) to define the behaviour that will be adopted in the coming farming year. In *Figure 9*b 'End' refers to the adoption of a decision by farmers, then natural resources recovery as shown in *Figure 9*a.

The learning process occurs in two different forms: an individually based and a Socially based learning depending on community interactions. For instance, agents at each timestep will evaluate the behaviour of others in the community and perform social/individual learning based on self or others production and status evaluation. Then the Adoption of the decision takes place, which considers a number of 7 mechanisms listed below, which have been selected based on literature research as representative of the environmental requirements and social dynamics that stand behind the adoption of a new practice:

1. Productivity factors such as natural resource and input availability are stored in patches memory and are evaluated by agents at the start of each run by comparison with an acceptance threshold. Input and natural resource availability is reduced by input used and natural resource used (Equation 1 and 2) and define the possibility to involve in one or another practice:

Equation 1 $input\ available_t = input\ available_{t-1} - input\ used_t$

Equation 2 $natural\ resource\ available_t =$

$$natural\ resource\ available_{t-1} - natural\ resource\ used_t$$

Input used and natural resource used determine crop production (Eq. 3):

Equation 3 $crop\ produce_t = input\ used_t * \frac{natural\ resource\ used_{t-1}}{100}$

Natural resources used is normalized by dividing to its max value. The factor represents resources degradation as a result of the performed practice.

2. In the Learning Processes agents perform voting schemes defining the propensity to involve in a certain practice. In social learning the intention of an agent to involve in traditional practices or CA is based on the evaluation of others with higher outcomes and status in the social network. Agents with higher status in the model are those farmers which have higher production and higher level of education. A social voting scheme is performed in this case defining the preference based on the more adopted behaviour among observed agents in the network (Eq. 4):

Equation 4 $Social\ Vote\ practice = \frac{(number\ of\ agent\ with\ sustainable - number\ of\ agent\ with\ traditional)}{total\ number\ of\ agent\ produce\ more\ than\ itself\ with\ higher\ education}$

If no agents with higher status are present in the network, the farmer will perform individual Vote practice based on self-yield variance. The preference in adopting CA or traditional practice refers to the acceptance threshold in relation to the variance. Values of yield variance above the threshold define the preference in adopting more sustainable practices, defining +1 in the Individual Vote practice.

Equation 5 $Variance\ crop\ produce = Var[crop\ produce_t, crop\ produce_{t-1}, \ldots, crop\ produce_{t-n}]$
$n = memory\ length$

In both learning processes agents vote 1 when preference is CA, -1 when traditional. Voting schemes are used in Final decision making (see below).

3. Adaptation propensity is performed by agents following the learning process in which a preferred behaviour is defined. Adaptation propensity is dependent on the individual factors of the agent in relation to power dynamics (affecting access to community resources and services), the level of education and the size of the household which strongly affects farmers propensity (Eq. 6). This process results in an *adaptation factor* equal to 1 when adaptation conditions are respected and 0 when not. The adaptation factor is then used in farmer's Final decision (Eq. 7) combined with the result of the learning process and defines the adoption of CA practices or the evaluation of the Risk (Eq. 8) when the adaptation propensity equals to zero:

Equation 6 $Adaptation\ propensity =$
$$gender + access\ to\ community\ resources + access\ to\ training\ +\ Household\ size$$

Equation 7 $Final\_adaptation\ =\ (individual/social\ Vote\ *\ Adaptation\ factor)$

4. Risk evaluation is set as final decision procedure of the timestep. This factor is representative of agent's perception of its capacity to face risk and uncertainty in agricultural production and results in the adoption of no cropping or traditional practices. Risk evaluation is based on

gender, the level of education, the effect of power spatial location in relation to centres and the results of individual learning process:

Equation 8 $$Risk\ evaluation = \ gender\ (*1) * \ access\ to\ community\ resources (*1) + access\ to\ training\ (*1) + \ individual\ Vote$$

5. The effect of power: in the model gender discrimination is represented by the exclusion from accessing community resources and services such as land and training with an effect on agent's Adaptation propensity to a new behaviour and Risk perception related to uncertainty;

6. The effect of status: agents interact in the social network with those with higher status, which means agents with higher production and higher education. This results in voting schemes that affect farmers propensity during the learning process;

7. Agents' spatial location: the spatial location of agents refers to the distance from training centres, in the model a male agent located in nearby areas to a centre can access the training and collect education concerning best practices, this positively influences the propensity to involve in Conservation Agriculture.

The decision process of farmers in the model is therefore driven by various factors related to individual conditions, power/status interactions and yield security factors so as shown in the *Figure 9*B diagram. During the learning process, the agent's propensity changes depending on self- outcomes and other's outcomes in the social network while the final decision takes into account farmers individual factors such as education level, gender, location, household size, status and power effects. In the last step of the tick (timestep) the environment recovers, and input are renewed depending on the agricultural behaviour adopted. The simulation stops when the number of runs reaches 10, 25 or 50.

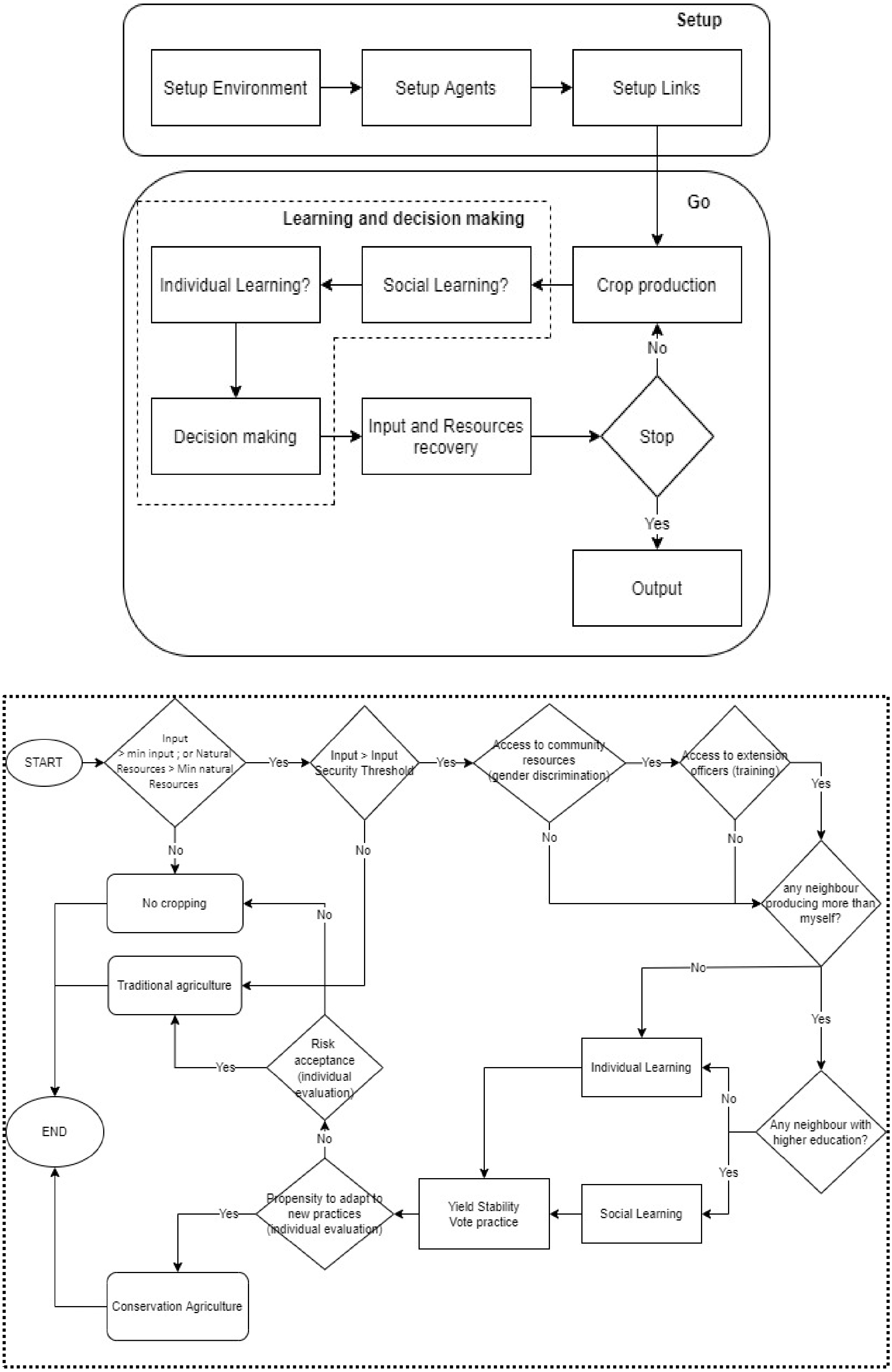

Figure 9 a) Flow Diagram of the model; b) Flow Diagram of agent's learning process and decision-making

1.5.3 Sensitivity analysis

1.5.3.1 OFAT Sensitivity Analysis

One Factor at a Time (OFAT) Sensitivity Analysis (SA) was conducted to validate the model against Social Learning Theories (Broeke et al., 2016). OFAT was selected as methodology to reveal the form of the relationship between the varied parameter and the output. The analysis consists of selecting a base parameter setting (nominal set) and step-wise varying one parameter at a time while keeping all other parameters fixed at their nominal values. The OFAT sensitivity analysis allows to investigate whether the response is linear or non-linear, or if there are tipping points where the output responds drastically to a small parameter change. The OFAT sensitivity analysis yields the investigation and understanding of the model mechanisms and allows to gain insight in how patterns and emergent properties are generated in the ABM, and examine the robustness of emergent properties. The analysis accounts for stochastic effects by running the model for the exact same parameter settings with a large number of replicate runs (here 25 replicates per parameter set were used). The following paragraph shows the steps taken for the SA.

The analysis starts by running the model with default values for each variable in order to investigate the model patterns using Netlogo. Then the change of one variable at a time is performed (see *Table 3*), in order to observe changes in the fraction of agent's adopting "sustainable" (Conservation Agriculture) farming. The variable is changed one value at a time to better understand changes. In this phase of the analysis Netlogo's BehaviorSpace was used with a set of 3 timesteps for reporting the model output: 10, 25 and 50 ticks. The output csv files are manipulated and transformed using Excel which was also used to visualise the output and perform linear regression. *R-squared* was performed using basic LR options in Excel to indicate the proportion of the variability in the dependent variable that is explained by model.

Table 3 Selected variables to validate the model against Social Learning Theories in the One Factor at a Time (OFAT) Sensitivity Analysis

Variables	Default values	Range	Step
Number of people	300	0-800	100
Number of links	3	0-6	1
Memory length	4	1 to 10	2
Yield variance threshold	2	1 to 10	1
Number of education centres	5	0 to 10	1

The table defines the set for the analysis and the ranges used in the OFAT. In the model field size is not subject to change. The number of people was selected to observe agents' density impact on Social Learning; The number of links was selected to observe the effect of social network links on the learning process. Memory Length and Yield Variance Threshold were selected to observe the impact of individual learning on social learning dynamics. Individual learning is performed by agents when no one in the network has higher status. In individual learning agents evaluate crop variance collected in memory and compare the value to the Yield variance threshold. When the threshold is exceeded, agent preference will be to produce CA. The number of education centres allows to explore the effect of external input on agent's behaviour. Since the size of the fields is fixed in the simulation an increase in number of centres refers to a density increase of centres. The output of interest concerns the fraction of farmers that are adopting "sustainable" behaviours.

1.5.3.2 Student t -test

An additional test was performed to evaluate the effect of gender inequalities on the model output concerning agents adopting *sustainable* practices. The model was run for 10, 25 and 50 ticks with two scenarios:

a. In scenario 1 only men can access community services, i.e., this is the basic model set-up;
b. To investigate the effect of possible gender equality, in the hypothetical scenario 2 both genders have equal access to community services.

The Student t- test is used to investigate if there is a statistically significant difference between the two scenarios.

1.6 An integrated approach of SD and ABM

Several frameworks are introduced to address productivity performance in the agricultural sector (Hulme et al., 2018). However, the performance predictions obtained using these frameworks often deviate from real performance. Static modelling (e.g., computer-based spreadsheets), differential equations, automata and process algebraic models, Bayesian networks, machine learning, neural networks, social network analysis and Monte Carlo methods are, unlike ABM and System Dynamic modelling, not able to model or simulate dynamic causal feedback among fundamentally different factors. Rather, predictive and simple statistical modelling, as well as mathematical algorithms that forecast the probability of future events, are useful for understanding certain aspects of complex systems at fixed time points and/or across one or more levels (Hulme et al., 2018). The use of CLD allows us to explore the structure of the system in which the agents are acting and the corresponding interdependencies and increased complexity that emerges from these relations. The diagram allows us to explain the known relationships among system components; however, it does not allow us to identify novel behaviours that may emerge over time as the system scales along various dimensions. In an attempt to model the complex system that represents this socio-economic agricultural system, we integrated an ABM that emulates the interactions among individuals with the dynamic variation of individual's propensity to behave according to the social constrains which characterize the system. The use of the two methodologies allowed us to explore additional factors affecting the overall output of the system and lays the foundations for an analysis that takes into account the role of behavioral dynamics in the success of targeted initiatives and actions, allowing for more effective interventions in the system.

2 RESULTS

2.1 Causal Loop Diagram

With the purpose of understanding the main drivers influencing subsistence production in eSwatini agricultural structure, a CLD (Vennix et al., 1996) of the system was developed using the Vensim PLE software, based on the data obtained from literature reviews and the results of interviews with COSPE NGO which acts locally supporting small-scale agricultural development in eSwatini.

In the model a number of intertwined dynamics is represented. 28 variables have been identified for the representation of the system, *Table 4* summarizes for each of these name and short description of its relevance i.e., the reason of its selection. The relationships that bind the variables in the system have been explored, results are reported in Appendix 1 in order to allow a fluid flow of the report, an example of the linking procedure among variables is shown in *Table 5*. The resulting CLD is represented in *Figure 10*. The elements of the diagram have been divided in four main topics related to the legislative framework concerning the availability and allocation of natural resources in the country (i.e. **Resources and private interests** marked in light blue), the economic participation of small scale producers in the market (i.e. **Rural means for development** marked in orange), policies and subsidies in the agricultural sector (i.e. **Legislation and policies** marked in pink), and the effect of infrastructural development (i.e. **Infrastructure development** marked in green), which substantially influence the dynamic of the whole system. Moreover, a set of variables was defined representing the boundaries of the system under analysis. The limits of the conceptual map are based on national dynamics, the implications of this choice will be mentioned in the discussion. The CLD illustrates feedback loops of eSwatini's agricultural industry performance demonstrating factors influencing system output and sustainability, these are reported in the final section of this paragraph. The arrow links in *Figure 10* form the feedback loops. This indicates that a given change kicks off a set of changes that cascade through other factors so as to either amplify ['reinforce' (R)] or push back against ['balance' (B)] the original change.

Table 4 Selection of variables representing the effect of socio-economic dynamics on eSwatini small-scale subsistence productivity.

Variable	Description	V#
SNL subsistence production	Farmer's objective under a subsistence system is mainly food security and is achieved through own production of inputs such as retained seed (Lucinda N. Dlamini, 2019). Farming techniques on SNL are almost exclusively traditional, using very simple tools and employing predominantly family labour and draught animals.	V1
Resources and private interests		
Water use	Competition for water resources in the country is a major issue. The irrigation sector in eSwatini uses approximately 96 percent of water consumed at a national level. Within the irrigation sector, over 90 percent of the water is used by the sugar industry (Mhlanga-Ndlovu & Nhamo, 2017).	V2
Water availability	Agricultural production takes place in an environment characterized by risk and uncertainty. This condition is especially true in arid and semi-arid areas where the water supply to crops from rainfall is variable and erratic (FAO, 2012). The strong dependence of small-scale farmers on the availability of natural resources, especially water, has become a critical issue when it comes to subsistence production at the household level (FAO, 2015b; IFAD, 2012).	V3
Rural water infrastructure development	In many areas of the country, irrigation is not practiced due to the lack of water sources in nearby areas (Mijinyawa & Dlamini, 2008). In the last two decades, the country has developed two main irrigation projects in an effort to reduce poverty and increase investment into pro-poor infrastructure projects to help rural households produce their way out of poverty through the commercialisation and intensification of irrigated agriculture (Njeim, 2018).	V6
SNL cash crop production	The development of small-scale irrigation systems in the southern African region has had significant investments in recent years to extend the participation of smallholder farmers in the sugar industry expanding within the region (N. S. Dlamini et al., 2014), as a result some farmers have increased production of cash crops on SNL, such as sugar, cotton, tobacco, and vegetables (Masuku, 2011) in order to increase incomes by integrating into the existing commercial market-oriented environment.	V7
Private irrigation schemes	Water is the key driver and a precious input to sugarcane production. All sugarcane produced is irrigated. Irrigation is the key water user in Swaziland as it takes up to 96% of total water consumption (Mhlanga-Ndlovu & Nhamo, 2017).	V8
TDL cash crop production for export	91% of the irrigated land in eSwatini is under the control of large domestic or foreign companies and used for the production of export goods such as sugarcane and cotton, which account for more than 60% of the country's total agricultural production (Njeim, 2018) and 24% of national merchandise exports in 2019 (Worldbank).	V9

Rural means for development		
Import of basic goods	eSwatini is a net importer of primary goods and satisfies its supply deficit almost entirely with products from South Africa. The country has never produced enough for total domestic consumption, eSwatini in fact, only produces enough to meet about 45% of its annual total cereal requirements (Mohammed and Dlamini, 2018).	V11
Farmers access to market as consumers	The country is a net importer of goods and satisfies its supply deficit almost entirely with imports from South Africa, where reduced regional harvest and higher international prices have the capacity to drive up prices, consequently inflating import costs for eSwatini with effects on the ability of the poorest groups to access the market as consumers due to their low purchasing power.	V12
Farmers competitiveness on price	The high cost of farm inputs such as seeds, fertilizer and hiring tractors for farm operations, which are provided by private companies related to parent companies in South Africa, is compounded for poorer farmers by the lack of access to short-term production credit and affects farmers competitiveness on market prices (Xaba & Masuku, 2012).	V13
Farmers access to market as traders	Low levels of development in rural infrastructures in terms of communication means and roads, limited access to market information and technological development, and access to services such as education and training concerning best practices and commercialization skills limit farmers participation to local markets. Moreover, although National efforts to include small holder farmers into local markets, low prices of imported goods remain a limit for small-scale commercialization due to the high cost of inputs prevailing in the country (Masuku, 2011; Xaba & Masuku, 2012).	V14
Access to education and training	The slow development of small-scale growers in Swaziland can be attributed in part to the inability of the Swazi farmers to respond positively to new ideas. For farmers to respond positively to new ideas, they must be properly educated on how best to apply the new ideas to their farming activities, more increased agricultural productivity depends primarily upon the acceptance of cultural and technological changes at the rural farm level (Dlamini and Worth, 2016). Education and training are essential resource input to the process of technological change, agricultural growth and commercial orientation of the farmers (Ndulo & Assié-Lumumba, 2020).	V16
Farming techniques and resources management	In order to improve communities' resilience and management of natural resources the Government of Swaziland adopted an approach that focuses on climate change adaptation through resilient agricultural practices. This has involved the introduction of climate smart agriculture (CSA) techniques such as conservation agriculture (CA), agroforestry (AF), the use of drought tolerant crops and the use of quality seed for specific ecological areas. The shift from conventional agriculture to CSA has the potential to intensify and stabilize food production by	V17

	engaging farmers in innovation and fostering new enterprises for income generation (FAO, 2019).	
Income from agriculture	Unreliable agricultural productivity coupled with escalating poverty levels in rural areas led some households to diversify their portfolio of income sources. Major income sources in rural areas are classified into on-farm, rural nonfarm, off-farm, and remittances (Mabaso et al., 2020)	V15
Crop yield	Yield is influenced by the ability of farmers to cope with agricultural needs in rural areas. Small scale farmers in eSwatini are faced by various constrains when it gets to increasing yield crop: lack of irrigation facilities, reduced access to input and machineries, and lack access to technology, innovation and training (D. V. Dlamini et al., 2019; Masuku, 2011; Uduji et al., 2018).	V22
Policies and legislations		
Cost of inputs	Inputs and agricultural tools available in Swaziland are provided by private companies related to parent companies in South Africa. eSwatini-based companies and individual farmers are prohibited from directly importing inputs and tools from South Africa, so they must purchase locally from the limited number of authorized suppliers. This makes inputs and tools expensive limiting farmers access due to their low economic availability (Worldbank, 2011).	V20
Access to input, tools and machineries	Most rural households do not have access to inputs due to the poor financial situation. The poor performance of the agricultural sector in eSwatini is attributable among other things to the increase in the prices of agricultural inputs that small farmers cannot afford (S. Dlamini et al., 2020).	V21
Access to financial credit	The role of credit in agricultural production is crucial because inputs such as seeds and fertilizers are purchased at the beginning of the production season, but returns are realized only at the end of the season. The provision of credit was considered an important tool for increasing the incomes of rural populations, mainly by mobilizing resources for more productive uses. The use of fertilizers and other inputs in Swaziland is limited by small farmers' limited access to credit (Worldbank, 2011).	V23
Land policy	The absence of a Land Policy concerning SNL is identified as a key constraint to the reorientation of agricultural production systems to enable small farmers to create wealth for themselves in eSwatini. One of the major constraints regarding land is that currently SNL cannot be used as collateral for sourcing financial credit on banks (Manyatsi & Singwane, 2019).	V24
Infrastructure development		
Access to information and technology	Farmers with access to information and technology have the ability to make informed decisions concerning production and marketing matters. Farmers would know the crop to grow (demand) and the market to supply. Techology adoption enables farmers to communicate easily with buyers and input suppliers and to access marketing information such as price (Bongiwe Porrie Dlamini-Mazibuko, S. F. , 2019).	V25

Schooling and extension training	Smallholder farmers in rural areas experience constrains in accessing formal education and training. Despite free primary school education is provided since 2005 for households involved in subsistence activities the opportunity cost of letting children being at school rather than being active in the household to assist with agricultural activities becomes a greater issue for some parents. In addition, higher education becomes costly making further education less attractive (B. Dlamini & Keregero, 2002a). Adult learners in rural areas have limited pathways to general education and training, to upgrade their skills, and to retool themselves for emerging opportunities (World Bank, 2010). In addition, smallholder growers should be provided by the MOA extension agents with support concerning improved farming techniques and training in business management skills, although, MOA extension officers in rural areas are often unable to support agricultural development and welfare increase (Worldbank, 2011).	V27
Investment in roads and transportation infrastructures	Rural roads are fundamental in supporting both rural and agricultural development to improve the socio-economic conditions of people, in order to facilitate the distribution of agricultural products and its accessibility to the population. Rural roads play a role in providing physical access. In fact, the agricultural production of the small farmers of Swaziland has as its final destination the main centers of the country, where it is distributed to the various local markets (A. K. & Kongolo, 2014).	V26
System's boundaries		
Climate changes	Even though drought events have been reported to be increasing in the southern African region, they remain poorly described in many localities and thus do not reflect that different areas experience different challenges with varying intensities. This is particularly true in a country like the Kingdom of Eswatini where the occurrence of drought in the past has resulted in serious adverse effects, especially in the agricultural sector. For instance, the 2015/16 season was dry across the country and sugarcane, which is termed "Swazi gold", suffered a 30% reduction in revenue. According to the study conducted by (Tfwala et al., 2020) in the country, droughts have increased in prevalence and severity after the year 2000, especially in the dry Lowveld, moreover, the study revealed that droughts are generally increasing in the country.	V4
Precipitation variability	The main water sources for Eswatini are surface water and groundwater. However, water bodies make up only 4% of the land surface area, which is about 160 km2 of the total area of 17,364 km2 (eSwatini, 2020). The major drought of 2016, when the country experienced rainfall of up to 65% below average, had significant impacts on reservoir storage. Storage at the Mnjoli Dam in the Manzini region declined to less than 5% of capacity, and resulted in an 80% reduction of sugarcane irrigation requirements at Simunye Plantation and other estates (eSwatini, 2016a).	V5
Availability of funds for public investments	The Regional Development Plan responsibility focuses on socio-economic development through proper regional development planning and co-ordination, empowerment and mobilisation of	V10

	people at local level. The programme was established in order to bring about sound, comprehensive, balanced and integrated regional development and coordination (Eswatini Government).	
Availability of production subsidies	The most common challenges faced by smallholder farmers include increasing cost of buying farm inputs such as seeds, fertilizer, chemicals, hiring tractor for farm operations. The benefit generated by policy may take different forms such as an increase in output-price, reduction in input-price, tax rebate, interest rate concession and/or direct budgetary transfer. In order for developing countries to achieve productivity that are financially viable by the small-scale farmers there is need to have adequate inputs and proper technologies.	V19
Institutional agreement, legal framework and good governance	The constitution of eSwatini was adopted in 2005. It outlines basic concepts such as the kingdom, the monarchy, protection and promotion of fundamental rights and freedoms, citizenship, the directive principles of state policy and duties of the citizen, the structure of the branches of government, and other functions of conduct. In the Kingdom of Eswatini the executive power is hold by the King, the prime minister, and the cabinet who exercise total executive authority. The judicial power is based on a dual system where one part consists of courts based on the western model and laws, while the second part consists of Eswatini laws and customs. From a legislative perspective law that must be passed by the king who has the power to deny every law in place and can recommend new laws to be installed.	V28

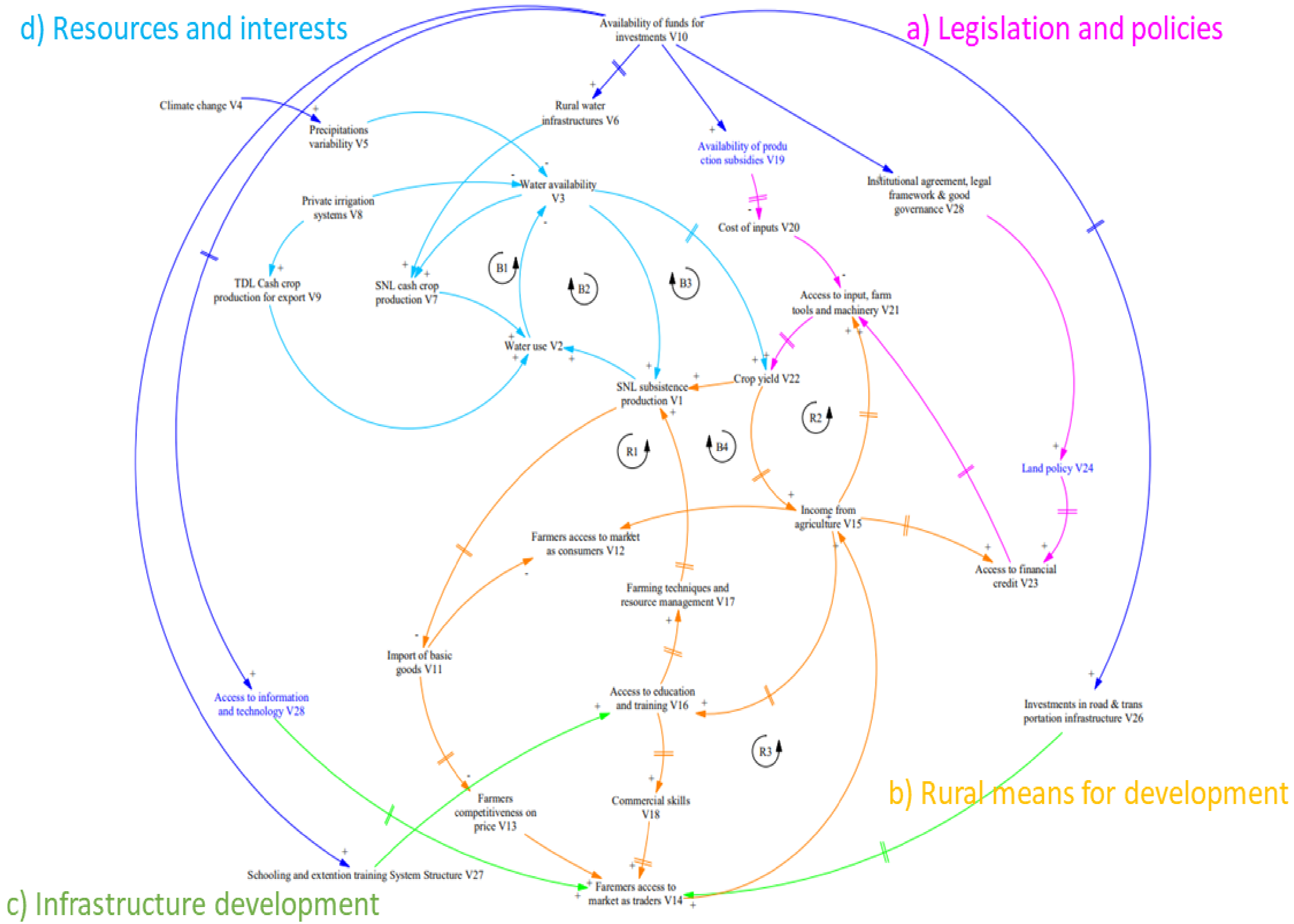

Figure 10 Causal loop diagram representing the selection of variables involved in small-scale subsistence productivity in eSwatini.

Table 5 Description of the connections among variables in the CLD (full Table in Appendix 1)

Linked variables	Link type	Explanation
V3-V1 Water availability / SNL subsistence production	L+	In Eswatini, smallholder farmers are found mainly on SNL where they practise mixed farming which involves growing crops and rearing livestock. Smallholder farmers are those farmers that produce crops and raise livestock on a small piece of land while using available resources which exclude expensive modern technology and machinery (Rugube et al., 2019). Water scarcity inflicts injuries on the social and economic lives of the populace. The spatial distribution of water is uneven throughout the country; water sources are often not located where there is demand, so it requires tanks and conveyor systems to carry the water, hence the need for storage. Sources of water available in many areas of eSwatini are related to natural basins, boreholes and rivers. The discharges from these sources often are low and get dried during the dry season. During this season, the inhabitants who have the means reach long distances from the community to find available resources. Rain water harvesting as a source of water have very little impact in some areas of the country which leads small holders to use water mainly for domestic and livestock and no irrigation activities. In many areas of the country, irrigation is not practiced due to the lack of water sources in nearby areas (Mijinyawa & Dlamini, 2008).In the last two decades, the country has developed two main irrigation projects in an effort to reduce poverty and increase investment into pro-poor infrastructure projects to help rural households produce their way out of poverty through the commercialisation and intensification of irrigated agriculture (Njeim, 2018). Although, the National Development Strategy (NDS) aim is to involve small-scale farmers in the expansion of the sugar industry in the region (as the most important segment of the agricultural export sector) by supporting small farmers in the transition from an agricultural system of subsistence to the production of income crops.
V1- V2 SNL subsistence production/ Water use	L+	The failure or loss of crop production due to pests and drought is a common factor for small holder farmers. The majority (92%) of community groups in Swaziland perceive water supply as a problem, and as such access to water on SNL for small holders is seen as fundamental for them to use their land resources to improve food security. The irrigation sector uses approximately 96 percent of water in Swaziland. Within the irrigation sector, over 90 percent of the water is used by the sugar industry. The construction of dams and infrastructures for the irrigation of rural areas has represented an element of importance for national development in the last 2 decades. In particular, two projects have been implemented whose objective is the supply of water in the rural and drought areas of Swaziland in order to guarantee a continuous supply and standard of living of the smallholder farmers by the commercialization and intensification of irrigated agriculture of sugarcane through a gradual withdrawal from the subsistence farming of maize predominately practiced in the region (Peter, 2011). In the study by the author, respondents were using the irrigation water system mainly for irrigating sugar cane grown on cooperative basis. Crop production on individual household plots continued to suffer crop losses due to drought.
V3-> V7	L+	In eSwatini, about 95% of the water used for irrigation is consumed by the Title Deed Lands (TDL), mainly sugarcane, equipped with irrigation systems, on large private estates. The objectives of the LUSIP National Irrigation Program aim to increase the efficiency of sugarcane value chains by integrating smallholder farmers into the commercial economy through the

Water availability -> SNL cash crop production for export	creation of farmer-run irrigation companies, while improving people's quality of life living within the PDA (Project Development Area) (Peter, 2011). In an article by (N. S. Dlamini et al., 2014), the authors highlight how the development of small-scale irrigation systems in the southern African region has had significant investments in recent years to extend the participation of smallholder farmers in the sugar industry, expanding within the region. In Swaziland, smallholder irrigation programs have been established with government help to increase smallholder incomes by integrating them into the existing commercial market-oriented environment. Despite national efforts to provide assistance to small farmers through extension services and sector specialists, small farmers lack marketing-oriented knowledge (Masuku, 2011).

2.1.1 *Feedback loops in the model*

In the diagram six causal feedback loops were identified mainly affecting the *Rural means for development* and the *Resources and interest* sections of the system. The analysis of the reinforcing and balancing feedback loops allows for the exploration of the model for patterns in their interconnected components. A description of the loops is provided in *Table 6*. In reinforcing loops the effect of a variation in any variable propagates through the loop and returns to reinforce the initial deviation. In balancing loops, the effect of a variation in any variable propagates through the loop and returns to the variable a deviation opposite to the initial one.

Table 6 Causal loops identified in the CLD diagram.

	N° of causal loop	Variables (V)	V_n°	Explanation
Balancing causal loops	Loop B1	Water use Water availability SNL cash crop production	V2 V3 V7	Balancing loop B1 refers to the role of SNL cash crop production in water consumption for farming. The development of the national irrigation scheme supports farmers in the transition to monetary agriculture. Profit pushes farmers to use their land to plant sugarcane, cotton or other cash crops which would decrease farming levels of primary goods.
	Loop B2	Water use Water availability SNL subsistence production	V2 V3 V1	Feedback loop B2 and B3 represent the effect of small-scale agriculture on wate resources and demonstrates how water shortages could act as a restriction for farming.
	Loop B3	SNL subsistence production Water availability Crop Yield	V1 V3 V22	
	Loop B4	Income from agriculture Access to education and training Farming techniques and resources management SNL subsistence production Water use Water availability	V15 V16 V17 V1 V2 V3	B4 shows the effect of improved farming techniques and natural resources management on small scale production. the effect of education and training allows for a reduced consumption and dependence of/on water by SNL

		Crop yield	V22	farmers positively affecting income from agricultural surplus.
Reinforcing causal loops	Loop R1	SNL subsistence production Import of basic goods Farmers competitiveness on price Farmers access to market as traders Income from agriculture Access to financial credit Access to input, tools and machinery Crop yield	V1 V11 V13 V14 V15 V23 V21 V22	R1 shows how an increase in production at the household level would reduce national dependence on imported primary goods such as maize and vegetables, allowing for a higher market share. Higher commercialisation in the sector affects farmers income with effects on access to credit and investments in land improvements which positively affects crop yields.
	Loop R2	Income from agriculture Access to education and training Commercial skills Farmers access to market as traders Access to financial credit Access to farm tools and machinery Crop yield	V15 V16 V18 V11 V23 V21 V22	Causal loop R3 represents the effect of education and specialisation on agricultural income at the household level. The acquisition of business skills contributes to farmers' participation in markets, the loop highlights the positive role of economic resources on crop yield as a consequence of accessing financial credit.

2.2 Agent-based model

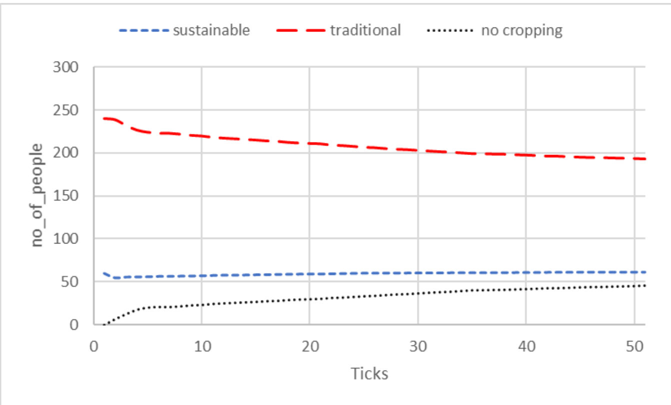

Figure 11 Agent's fraction adopting each of the 3 behaviours, with variables defined in default values

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The ABM simulation results can be seen in *Figure 11*. Each tick is representative in the model of 1 farming year therefore the simulation is run to a max of 50 ticks, as more would be unrealistic since many conditions and dynamics may change over time; in fact, it is reasonable to assume the system will change in a time period that is shorter than 50 years. The long-term simulations mainly serve to get an estimate of the possible rate of change in the farmer community towards more sustainable practice. The patterns show an initial condition in which agents evaluate the availability of input to involve in any farming practice, if not available farmers will change to *no cropping* behaviour. Next, agents learn as a consequence of the interaction with training centres located in nearby areas, for which an initial increase in farmers adopting sustainable can be seen. The results of agent's learning spread in the network through social learning, respectively slightly decreasing agents adopting traditional management. Sustainable behaviour reaches a stable pattern during the simulation. Agent's learning process defines the propensity of an agent to involve in traditional, sustainable or no cropping behaviour depending on self and other outcomes in the network, although the patterns of stability shown by sustainable farmers over time and the decrease of traditional farmers which mainly add to no cropping after a defined timestep, can be explained considering individual factors which strongly affect agent's final decision.

Sensitivity Analysis Boxplots are shown in *Figure 13*, while R-sq (linear fitting) and its p-values (probability of data occurring under the null hypothesis) are shown in *Table 7*. For all variables the distribution of the residuals was tested to evaluate the validity of the fitting procedure. A random distribution of the residual points around the horizontal axis indicate that a linear regression model is appropriate for the data although various data show relatively high values for all dependent variables (see Appendix 3 for Residuals plots). Residual plots for Number of centres at all timesteps show an increasing variance of residuals related to the increase in centres density in the model (*Figure 12*). The Residuals plot for N° of centres at the 3 timesteps is reported below.

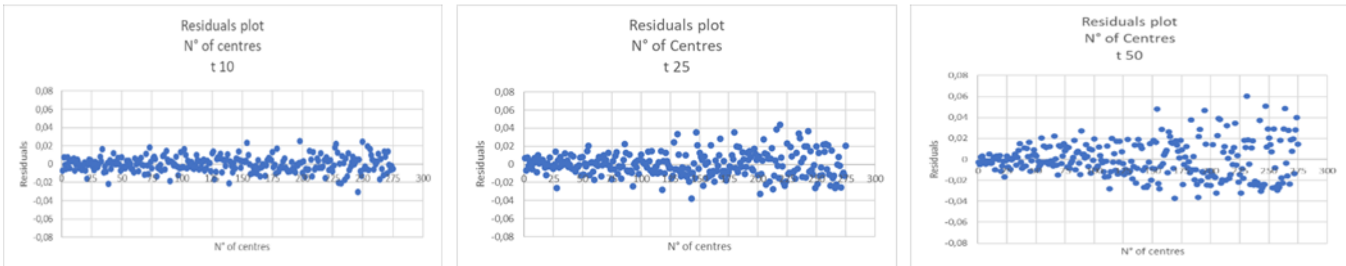

Figure 12 Residuals plots for N° of centres at all timesteps: 10, 25, 50.

2.2.1 Results obtained from the SA

The *Number of people* involved in the simulation does not impact the output as defined by extremely low R-sq values and is confirmed again with p-values higher than 0.05 (see *Table 7*). Similar is the effect of *Number of links* and *Memory length* in all timesteps considered except for *Number of people* at t = 10 and *Memory length* at t = 50 for which p-values lower than 0.05 were measured meaning that the model doesn't explain much of variation (R-sq of respectively 0,030 and 0,035) but the regression is still significant and fits statistically the data (p-values of 0,017 and 0,038). All mentioned variables show to have low fit with linear regression (R-sq).

Yield Variance Threshold shows a low fit with linear regression, again not showing any evidence of an effect of the parameter on the output. P-values for Yield Variance Threshold lower than 0.05 define that the model explains well the variation of the dependent variables.

Number of Education Centres show an existing but low fit with linear regression and present p-values lower than 0.05 again confirming the statistical significance of the regression in relation to the data. An increase in R-sq values for *Number of Education Centres* can be observed with higher timesteps. Also in this case, the model fits well the data as confirmed by p-values lower than 0.05. See *Table 7*.

Table 7 R-Squared and p-value from linear regression of sensitivity analysis

	Simulation timestep	**R-squared**	**p-value**
No of people	**Ticks 10**	0,0297	0,01462
	Ticks 25	0,0015	0,5884
	Ticks 50	0,0093	0,1736
No of links	**Ticks 10**	0,000148	0,882
	Ticks 25	0,002485	0,5446
	Ticks 50	0,00072	0,75
Memory length	**Ticks 10**	0,01215	0,22
	Ticks 25	0,007452	0,34
	Ticks 50	0,0346	0,0377
Yield variance threshold	**Ticks 10**	0,04	0,001
	Ticks 25	0,073046	1,47207E-05
	Ticks 50	0,042607436	0,001027864
Number of education centres	**Ticks 10**	0,249116907	9,9139E-19
	Ticks 25	0,279329	3,44756E-21
	Ticks 50	0,352676	1,33362E-27

Figure 13 Box plots for Sensitivity Analysis results: number of people, number of links, memory length, yield variance threshold, number of education centres. Each simulation was run at 3 timesteps: 10, 25, 50 ticks, with 25 replicates for each unique parameter set.

2.2.2 Results obtained from the Student t-test

An additional Student t- test was performed using Excel to evaluate the effect of gender inequalities on the model output concerning agents adopting Sustainable practices. The statistical results of the t-test are reported in *Table 8*. The absolute value of the t-statistic changes in the 3 timesteps under analysis:

1. Timestep 10: the absolute value of the t-statistic is 2,33 which is greater than the critical value of 2.02, it can be concluded that there is a statistical significance in the output of the two simulations with and without gender equality.

2. Timestep 25: the absolute value of the t-statistic is 4,34 which is greater than the critical value of 2.02. It can be concluded that also in this case the values highlight the existence of a statistically significant difference in the output of the two simulations with and without gender equality.

3. Timestep 50: the absolute value of the t-test is 0,13. In this case the difference between the simulation in the two conditions do not show a statistical significance in the difference among values.

Table 8 T-test performed at 3 timesteps (10, 25, 50) to investigate the effects of gender discrimination on the output. The model was run in nominal values for the 2 scenarios

t-test 10 ticks	*gender discrimination*	*gender equalty*
Mean n_of_sustainable	56	58
Variance	7,07	8,18
Observations	25	25
Difference hypotized between means	0	
gdl	48	
Stat t	-2,33	

t-test 25 ticks	*gender discrimination*	*gender equalty*
Mean n_of_sustainable	57	60
Variance	5,68	8,71
Observations	25	25
Difference hypotized between means	0	
gdl	46	
Stat t	-4,34	

t-test 50 ticks	*gender discrimination*	*gender equalty*
Mean n_of_sustainable	59	59
Variance	10,79	8,54
Observations	25	25
Difference hypotized between means	0	
gdl	47	
Stat t	0,13	

3 DISCUSSIONS

The factors influencing the productivity and choices of subsistence farmers in eSwatini were analysed through the use of two models: a causal diagram was used to identify the variables that influence the output from a social and economic point of view. On the other hand, the development of a model based on agents has made it possible to include social behaviours such as the effects of power and status and the influence of traditional laws, as drivers of the adoption of innovative agricultural practices by eSwatini farmers.

3.1 Meaning of the Causal Diagram

An extended interpretation of the Diagram should be understood as follows.

Low rural development of infrastructures and services limit the ability of farmers to access up-to-date agro-climatic information, new technologies, training, market information and production means, with effects on small-scale productivity in rural areas (A. K. & Kongolo, 2014; M. M. Dlamini & Worth, 2019; World Bank Group, 2020). In eSwatini smallholder farmers are found mainly on public land (SNL) where they practise mixed farming which involves growing crops and rearing livestock. Smallholder farmers are those farmers that produce crops for subsistence and raise livestock on a small piece of land while using available resources which exclude expensive modern technology and machinery (Lovemore M. Rugube S. P., 2019). The strong dependence of small-scale farmers on the availability of natural resources, especially water, has become a critical issue when it comes to subsistence production at the household level. Communities in low and middle-income countries in fact, are heavily dependent on natural resources, which makes them especially vulnerable to impacts of climate change (Parry et al., 2007). Rain water harvesting as a source of water have very little impact in some areas of the country which leads small holders to use water mainly for domestic and livestock and no irrigation activities. In many areas in fact, irrigation is not practiced due to the lack of water sources in nearby areas (Dlamini, 2008). The development of a comprehensive water resources development program is seen as a key drive for planning the reorientation of agricultural production systems to enable farmers to create wealth for themselves

(FAO, 1997; Njeim, 2018; Turner, 1994). The national development of water schemes in the country and the access of small subsistence farmers to the service although is subjected to the transformation of subsistence farms into commercial farms of irrigated land producing cash and food crops for national and international markets, the program was introduced by the Government with the aim of improving incomes and reduce poverty. In an article by (N. S. Dlamini et al., 2014), the authors highlight how the development of small-scale irrigation systems in the southern African region has had significant investments in recent years to extend the participation of smallholder farmers in the sugar industry, expanding within the region. In Swaziland, smallholder irrigation programs have been established with government help to increase smallholder incomes by integrating them into the existing commercial market-oriented environment. Eswatini's agricultural sector is the second largest contributor to the economy after the manufacturing sector. Commercial agriculture is dominated by canned fruit, beef production for export and sugarcane production, mainly on TDLs (Tittle Deed Lands) which are large private estates practicing intensive highly mechanized agriculture and provided with irrigation facilities which account for the consumption of over 90% of the water used for irrigation in the country. Although, the expansion of the sugar industry in the country over the last years is mostly attributed to the entry of smallholder SNL sugarcane growers which represent a key for the sustainability of the overall industry (N. S. Dlamini et al., 2014). Low productivity levels on SNL and governmental pressure for a transition of subsistence to commercial farming affects the availability of primary needs, and contribute to make eSwatini a food deficit country (WFP, 2021). Maize remains the important staple food crop grown on Swazi Nation Land for subsistence purposes and food security (MOA, 2016). It is also the measure of food security in the country (FAO, 2005b). However, though a substantial number of rural households produce it, the country has never produced enough maize for total domestic consumption. Food production deficits lead to substantial imports from South Africa to meet local food needs (MOA, 2016) this means the country is more exposed to global developments in markets, which can result in a widened trade balance for the importing country (Sacolo et al., 2018). Price volatility in a stable food like maize is particularly important for Swaziland in that most Swazi are poor. It is known that poor segments of society spend most of their income on food. Therefore, unpredictable spikes in stable food prices that form major caloric intake become an important food security issue especially for poor countries (Sukati, 2013).

Households' access to food in fact, is strongly dependent on the occupation status since a large proportion of the food consumed is purchased (Mabaso et al., 2020), although the labour force participation in the country is still one of the lowest in Africa (51.3 per cent) and most of the jobs remain informal, with low-productivity and low-skills development (UN, 2017) resulting in low purchasing power for households. The effects of a supply chain heavily dependent on imports can also be observed in the fraction of farmers who participate in the local market through the sale of their products. Low production on public lands is partly attributable to the scarce availability of inputs and machinery aimed at supporting agricultural productivity and development. In fact, most of the inputs and agricultural tools available in eSwatini are provided by private companies related to parent companies in South Africa, this limits competition with imports in the market and generally makes inputs and tools expensive and not accessible to smallholders due to their poor financial situation (Rugube et al., 2019). The high cost of inputs and tools is compounded for poorer farmers by the lack of access to short-term production credit which plays an important role in increasing agricultural productivity in developing countries such as eSwatini (Worldbank, 2011). According to (Muhammad L., 2003) the growth of agriculture depends on an increased use of agricultural inputs, technological changes and technical efficiency. In less developed countries such as eSwatini, where savings are negligible especially among small farmers, agricultural credit becomes an essential input along with modern technology for greater productivity. In eSwatini small-scale farmers' access to credit is limited by the possibility of using SNL as a guarantee for bank loans (Absalom M. Manyatsi, S. S. , 2019) since there is no written evidence of land use rights concerning SNL allocation. Public land allocation follows customary law whereby the householder approaches the traditional chiefdom authority under which he undertakes to request a piece of land to build a farm and grow crops. The head of the family is granted the rights to use the land and not the property as it is common land (Manyatsi & Singwane, 2019). Rural dynamics in eSwatini are strongly dependent on the figure of the local chief, who plays a major role in the management of rural resources in the name of the king and represents a reference for customs, traditions and justice at the community level (Sallinger-McBride & Picard, 1989). Limited access to credit combined with low levels of development in rural areas in terms of communication means limit access to market information and technological development, and access to services such as education and training concerning best practices and commercialization skills, which would positively contribute to income in rural areas (M. M. Dlamini & Worth, 2019). The slow development of small-scale growers in Swaziland can be attributed in part to the inability of the Swazi farmers to respond positively to new ideas. For farmers to respond positively to new ideas, they must be properly educated on how best to apply the new ideas to their farming activities, more increased agricultural productivity depends primarily upon the acceptance of cultural and technological changes at the rural farm level (Dlamini and Worth, 2016).

3.1.1 Feedback loops in the model

The results of the CLD representation identified feedback loops of eSwatini's agricultural performance in public land demonstrating factors influencing system output and sustainability. Using the criteria proposed by (Roxas et al., 2019), critical variables were investigated and a potential leverage point from the CLD was selected. Access to education and training is a common cause of multiple effects in the system, which are farming techniques and resources management (B4) and commercial skills (R2) which results in a relevant influence over the whole CLD. R2 represents the effect of education and specialisation on agricultural income at the household level. The acquisition of business skills contributes to farmers' participation in markets and according to (Bongiwe G. Xaba & Micah B. Masuku, 2013) plays a critical role in meeting the overall goals of food security, poverty alleviation and sustainable agriculture, particularly among smallholder farmers in developing countries like Swaziland. The loop highlights the positive role of economic resources resulting from market participation on crop yield as a consequence of access to financial credit, which represents a crucial factor for the development of the agricultural sector (Worldbank, 2011). B4 shows the effect of improved farming techniques and natural resources management on small scale production. One of the major factors affecting small scale production concerns the need to adopt Climate resilient agricultural practices in order to improve communities' resilience and management of natural resources (FAO, 2019). The effect of education and training allows for a reduced consumption and dependence of/on water by SNL farmers positively affecting crop yield. Apart from causing multiple effects, the increase in the stock of access to education and training can be influenced by an intervener, in fact, investments by governmental institutions in providing support through extension officers can increase the stock of actors accessing the service. Finally, the variable was selected as critical since the stock of access to education and training is independent from other variables in the CLD because, as the impact of a higher stock of access to education and training manifests, accrues, and reaches a certain threshold, the system can experience significant and irreversible changes.

3.2 Agent based modelling

The Agent Based Model was used to investigate the effect of social factors on the adoption of agricultural innovation. In the model social interactions among agents and the effect of socio-cultural dynamics (Bandura, 1977) are assumed as drivers of knowledge share and diffusion in rural communities and therefore affecting the propensity of agents in the adoption of new more sustainable behaviours. In this context the adoption of more sustainable practices (Conservation Agriculture (CA) practices) is representative of short-term and long-term adaptation to harsh environmental conditions. Short term adaptation refers to the capacity of increasing food production to face food insecurity issues; while long-term adaptation refers to the improved management of natural resources such as water and soil which allows an increase in resources availability over time while improving the availability of environmental services such as soil fertility and soil water retention with effects on crop production. The model therefore aims at addressing the investigation of the social factors affecting the rate of knowledge diffusion in the system as an indicator of how 'fast' the system can change given the described conditions of inequality and limited development.

The model was explored through the use of One Factor at a Time (OFAT) Sensitivity Analysis (SA) and the Student t-test in order to validate it against Social Learning Theories. In the analysis the output considered concerns the number of individuals who adopt Conservative Agricultural practices as a response to social interactions. The behavior of the model was analyzed in 3 different timesteps for each analysis:

a. The simulation stops at t = 10
b. The simulation stops at t= 25
c. The simulation stops at t= 50

In the model each timestep (*tick* in Netlogo) is representative of a farming year.

The main results of the SA show no evidence of the effect of *Number of people, Number of links, Memory length* and *Yield variance Threshold* on the overall behavior of the dependent variable and is represented in the analysis by extremely low R-sq values.

On the other side *Number of centers* results show R-sq values of respectively 0,25; 0,29; 0,35 for each timestep highlighting the effect of the independent variable on the output.

For all variables the distribution of the residuals was tested to evaluate the validity of the fitting procedure (see Appendix 3). A random distribution of the residual points around the horizontal axis indicating that a linear regression model is appropriate for the data, although various data show relatively high values for all dependent variables. Again, specific patterns are observed for Number of Centres residual plots for which an increase in centres density in the field results in an increasing variance of the residuals. This can be explained in relation to the dependence of the simulation on the random initial distribution of agents and centres in the system which affects agent's spatial location in relation to centres in each simulation. Increasing the number of centres in the system leads to an increase in the rate of knowledge spread among farmers rather than an increase in the fraction of people directly involved. This implies that the presence of education centres is a key factor in knowledge spread although the main effect is reached as a result of knowledge diffusion through informal channels in the network, again affecting the adoption of new practices as a result of community interaction which influences the overall community resilience. The adoption of adaptation strategies and resilience at the farm level can therefore be seen as rising from communities rather than singular individuals.

The Student t-test was performed to evaluate the effect of gender inequalities on the model output concerning the adoption of Sustainable practices. The model was run with and without gender equality. The statistical results of the T-test change in the three considered timesteps. At t = 10 and t = 25 the values of the t-statistics highlight the statistical significance in the output of the two simulations with and without gender equality highlight an increase in the spread of CA adoption in the scenarios with no gender discrimination for which the rate of spread is faster than in the non-equal scenarios.At t= 50 the difference between the simulation in the two conditions do not show a statistical significance in the difference among values at higher timesteps in fact the transient behaviour has been passed and for both scenarios the reach of a steady state can again be observed. The results of the comparison between the two scenarios highlight the key role of gender discrimination in the rates of knowledge spread in the system which leading to slow patterns of innovation adoption affecting the overall capacity of the community to face uncertainty and adapt.

Social Learning theories (Bandura 1977) stand as the theoretical base of how the individual decisional process takes place. The theory assumes an iterative feedback between the learners and their environment which means the learner changing the environment, and these changes affecting the learner. In Social Learning models, individuals apply multiple observations to reach a general conclusion which is then based on personal experiences and the behaviour and experiences of others in their network. Similarly, Rogers' 1995 innovation diffusion theoretical perspective identified information as a key factor influencing adoption decision making. Other authors (Jager et al., 2001; Rogers, 1995) state that adoption is influenced by many factors such as socioeconomic, environmental and mental needs, and knowledge about the technology and individual perceptions about the methods used to achieve those needs (P.H. Thangata & J.R.R. Alavalapati, 2003). According to the theory behind my ABM model, the results shown by the SA in relation to the effect of the structural components (number of people and spatial links) and rational behaviours (memory length and yield variance acceptance) on the spread of knowledge and the adoption of innovation highlight the influence of other factors affecting the behaviour of the agents, this factors in the model are related to the cultural sphere of the individuals. (Eseonu & Egbue, 2014) emphasize the role of culture in influencing attitudes and behavioural intention towards technology and innovation, which have been shown to affect decision to adopt. According to previous works, evidences of the role of gender discrimination in the spread of innovation in communities are observed in model results. The exclusion of women from social interactions strongly impacts on the rates related to the spread of new behaviours, in fact the role of the community in the spread of knowledge represents a key factor in the overall capacity of the system to adapt rather than being dependent on single individuals. Women in eSwatini represent the majority of the working force in agriculture as a result of social exclusion from other types of jobs in the community. Women face harsh conditions due to their limited access to resources and training. The propensity of women in the ABM model is in fact strongly influenced by others in the network producing CA although the decision-making *confirmation phase* (Rogers 2003) which represents the last step before adopting defines social exclusion of women from the possibility of adopting innovation.

The limited access of men to education centres due to spatial distance is again a strong factor of lack in innovation adoption by male farmers. (P. M. Dlamini, 1993) highlights the role of training as an essential resource input for all contributors to the process of technological change and agricultural growth. In the model a growing number of conservation agriculture adoption can be observed with the increase in centres density in the system, so as confirmed by the results of the SA analysis, in fact an increase in the number of centres leads to a higher rate of knowledge diffusion among male farmers with strong affects in the learning process. The number of individuals adopting CA increases as a result of social learning until a steady state in reached. The reach of a steady state value is common in all simulations at all timesteps, this occurs as a consequence of the physical and cultural exclusion of some individuals to accessing knowledge. According to the t-test analysis, in fact the results observed at t = 10 and t = 25 highlight an increase in the spread of CA adoption in the scenarios with no gender discrimination for which the rate of spread is faster than in the non-equal scenario. By t= 50 the transient behaviour has been passed and for both scenarios the reach of a steady state can again be observed.

3.3 Validation of the CLD and ABM

When modelling complex systems there are a number of issues that need to be addressed.

The CLD approach presents limitations. Causal loop diagrams provide a broad picture of the system's causal structure, however, a CLD should be combined with a simulation model to infer the system's dynamic behavior and its drivers. The CLD represents "dynamic hypotheses" that explain the system's behavior as a result of its causal and feedback structure; then, a simulation model enables *testing* these hypotheses to infer the causes of system behavior (Blair et al., 2021). Although, given the breadth of the system representing complex social and economic phenomena, which are represented in the study though synthetized symbols, variables in the diagram (*Table 4*) the validation of the modelling is not possible at all. In order to verify the consistency of the representation, and therefore its applicability in real world systems, other authors make use of the mental models of all involved stakeholders, by collecting opinions and perceptions of how the system works, barriers to success, system drivers and possible strategies, and used them in a model-relevant direction. The interaction with groups of experts in this phase assumes relevance (Banson et al., 2015; Blair et al., 2021). In the present study, the comparison with professionals working in the sector (COSPE NGO) made it possible to partially determine the consistency of the models, both CLD and ABM. The CLD was also validated against the existing evidence about smallholder farmers conditions in eSwatini from both published articles and white papers, as it is representative of both practitioner and academic knowledge. This was important as a check against a possible “echo chamber"; that is, to ensure we were capturing the “true" system as closely as possible and not merely the individual perceptions of it. Research has shown that people’s inferences can be biased by their prior beliefs and attitudes. That is, they can engage in motivated reasoning: when solving a task, they choose the beliefs and strategies that are more likely to arrive at conclusions that they want to arrive at (Blanco, 2017). In the specific context of studies that analyse complex social systems which present different feature from the traditional framework most familiar to us, the occurrence of cultural bias can strongly influence our interpretation of the acquired information. In this context assumes relevance the investigation of the factors which could falsify the proposed representations. Falsifying a cognitive model relies on showing that it is unable to account for a specific effect of interest. Although, in the present study given the breadth of the systems, limited record-keeping by system actors, and constrained data collection resources of development actors and governments, there are limited quantitative data available. This strongly influences the validation of the CLD in its various parts highlighting the need to develop approaches that mitigate the disadvantages of relying on CLDs alone, without requiring the data, time, and resources to build a full-fledged simulation model, an overview on related theories is given by (Blair et al., 2021).

Agent based modelling shares various of the issues related to the representation of complex systems in CLDs. ABM is a valuable tool to understand socio-ecological systems because it can represent the behaviour and interactions of organisms, human actors and institutions. ABMs have therefore been widely used to study complex systems (Berger & Troost, 2014; Kremmydas et al., 2018; Zheng et al., 2013). However, because of their nature, this systems are often difficult to parameterize and analyse, which can limit the models’ usefulness (Schulze et al., 2017). A particular attention is given to the representation of human decision-making. Here, interdisciplinary collaboration among behavioural economics, social psychology and agent-assumes relevance. This can improve the availability of empirical data on decision processes, the understanding of how humans make decisions and how these decisions can be formalized in models (Schulze et al., 2017).

In the present study, the model was firstly validated by discussion with stakeholders involved in local projects of farm resilience against climate change, i.e COSPE Ngo. The validation process involved 3 elements of COSPE staff in eSwatini, including 2 local guys involved in the activities. The interview took place via Skype and the questions proposed concern the social sphere of individuals. Particular attention was paid to the role of information centers in rural areas, to the exclusion of women as a result of factors linked to the tradition and agricultural behavior of individuals with regard to the adoption of new practices. The results of the interview confirmed the already investigated literature reinforcing the assumptions introduced for the realization of the model.

The model results were further validated by comparing Sensitivity Analysis results with the Social Learning Theory. The model results align with the Social Learning framework. The behaviour of agents in the model is not influenced by Number of people, Memory length, Number of links and the Yield variance threshold. On the other side the results highlighted the role of education centres in the system as a starting point for the spread of knowledge in the system through informal learning practices (i.e., social learning).

3.4 ABM code Verification

The model testing was performed by peer review by a MSc student involved in the Resilience Team at WUR (Wageningen University & Research). The verification highlighted few bugs in the model, mainly related to the yield stability factor, which equation was inadequate to represent the element. This has been observed and edited to a new equation named “intention of farmers” which allows to keep track of the propensity of farmers as a result of the learning process and before the final decision adoption.

3.5 Contribution and future development of the models

3.5.1 Causal loop diagram

The United Nations (UN) Sustainable Development Goals (SDGs) are a “call to action” to end poverty, eliminate hunger, enhance equality, widen access to water, energy, and education, and achieve many other important milestones for humanity (The UN General Assembly 2015). Meeting the SDGs will require coordinated action and investment by national governments, non-governmental organizations (NGOs), the private sector, and civil society (United Nations 2020). This is a massive challenge, not least because these goals seek to address a set of intractable problems with multidimensional causes that intersect and influence one another (Lim et al. 2018, Nilsson et al.

2016). Achieving the SDGs will require adapting or redirecting a variety of very complex global and local human systems. As such, it is the development of a basic set of tools to understand the dynamics of these systems: how a system behaves over time, what drives its performance, and where interventions could create positive change. The system thinking approach provides insights into the structure and behavioural patterns of organisations helping to reveal the root causes of challenges, plan the future, reduce risk, anticipate delays and prevent significant unintended consequences(Banson et al., 2015). Systems approaches have been used in a wide variety of geographies (such as Ghana, Rwanda, Ethiopia, and Uganda) and development sectors (including health, agriculture, and democracy and governance) (Blair et al., 2021) giving rise to a new way of thinking required when concerning technical aspects of managing economic development and challenges (Banson et al., 2015). A systemic approach to strategic agricultural management implies that the human and natural environments make up a holistic system comprising individual components that are interconnected and affect each other, therefore affecting the whole system. Most of the existing tools for designing, monitoring, and evaluating development interventions are inadequate for analysing the dynamics of such systems. (Blair et al., 2021). This study fits into the context of the systems approach to the management of social, economic and environmental issues, with the aim of highlighting the use of the methodology in supporting decision-making processes, serving as a complementary tool for stakeholders and organizations to analyze and test the possible outcomes of different interventions by identifying system's components and their interactions, and observing what would happen to the system as a whole when a particular strategy or combination of strategies is implemented, before any time or money is invested in implementation (Banson et al., 2015). This will help to minimize the waste of scarce resources while facing complex globally-shared issues.

Future developments of the CLD would imply the active participation of the stakeholders involved in the system's specific areas. This would allow to identify, on one hand, the effect of limited field information and data and on the other hand, to verify the occurrence of cognitive biases in the interpretation of the system's dynamics and thus providing a validation to the modelling and allowing for further quantitative implementations.

3.5.2 Agent-based model

The results of the model highlight the effect of discrimination on the rates of change of the system. Gender inequalities in the agricultural sector represent a limit for agricultural production and development in various areas of the world (Huyer, 2016) (Seebens, 2011) (Timothy, 2006). The role of women in agriculture has grown in the last decades. Women active involvement in food production highlights their importance in sustaining and improving food security at various levels, first of all, the household level. The distribution of work based on gender is still common in many areas of the world and has led to an increasing participation of women in the rural agricultural sector as a result of men migration to the urban areas in search of waged jobs (Mabundza, R., Dlamini, C. S., & Nkambule, B. , 2014). Women therefore today represent the majority of the rural agricultural population in many parts of the world, including eSwatini (S N Odurukwe, 2006) (FAO, 2011) (Salam A. and Dlamini M. M., January-March 2011). The growing involvement of women in the sector and at the same time the limited access to productive resources, opportunities and services as a result of gender discrimination poses a major issue that must be addressed in the view of the need to innovate agriculture behaviors in the transition to more conservative agricultural practices, which appears necessary especially in those areas strongly affected by climate change. Various developing countries in the world are investing in the transition to more ecological agricultural practices in rural communities in order to tackle food insecurity issues related to their strong dependence on environmental conditions (IISD, 2019). However, the adoption of innovative practices by small rural farmers has not had the expected success in several areas (Nyanga, 2012). The factors that influence the adoption of new behaviors by small farmers is currently a topic of great interest (Niles, 2015).

The aim of this study is to contribute to the knowledge gap concerning these factors. The suggestions from the analysis of the Agent based model results are mainly highlighting the effect of gender inclusivity in speeding up the rate of adaptation to new measures against the negative effects of climate change on eSwatini agricultural output. Training and education centers in rural communities are often not available representing a strong limit for the transition to new behaviors by smallholder farmers (World Bank, 2011). The lack of formal education enhances social learning as the main means through which information is propagated in communities. Gender inequality in this context represents a strong limit to the diffusion of new practices, strongly influencing subsistence agricultural production, food security and agricultural development in the different areas (Mabundza, R., Dlamini, C. S., & Nkambule, B. , 2014), with effects on the diffusion rates of innovation and consequently on the capacity of system to cope with unexpected changes.

For future developments of the model, the investigation of a more generic rural learning system could be approached, i.e., investigation and inclusion in the model of the main behavioural features shared by most of the learning systems in similar conditions, without focusing on the specific characteristics of any particular system. On the other side, different shocks could be included in the design of the model to which the simulated agents respond. i.e., shocks related to climatic conditions and environmental degradation. This would allow to further investigate social dynamics in the context of resources management and policy interventions.

4 CONCLUSIONS

In this study, a causal loop diagram (CLD) was used for the investigation of the cause–effect relationships among the socio-economic components affecting eSwatini's small-scale agricultural production. The qualitative variables that influence the dynamics of the system were identified. A set of 28 variables capable of describing the performance of small-scale agricultural system in eSwatini was selected, and six feedback loops observed. Among these, one has been identified as a potential leverage point, representing a possible area of intervention which could affect the dynamics of the whole system. The critical variable in the study is represented by the stock *access to education and training*, which through the action of the feedback loops interacts with and influences multiple areas of the system. Interventions are suggested in this direction. The role of social factors in the adoption and spread of innovative practices in communities was analysed through the use of an agent-based model (ABM). In the model social features such as power/status relations are included in order to explore the factors affecting the diffusion of knowledge and the adoption of new behaviours in rural communities in eSwatini. According to the model results the social sphere of individuals represents a main factor on the spread of knowledge and the adoption of innovation. Adaptation in these terms refers to the adoption of practices which allow a reduced dependence of farmers on the availability of critical environmental resources that limit agricultural productivity (i.e., adoption of Conservative Agricultural practices). The study highlights the role of education and training as an essential resource input for all contributors to the process of technological change and agricultural growth. The Government should play a major role in providing smallholder growers with some training in addressing issues of concern to farmers, in order to support the transition to a more sustainable use of scarce resources and improve their yields. Moreover, the study sheds light on how resilience can be seen as rising from communities rather than singular individuals. The ABM results point to gender equality as an important factor to promote the uptake of innovative practice and thus improvement of the adaptation against adverse external conditions at the community level. These results highlight the need of addressing research in the investigation of the boundaries which allow a system to share information among its actors in the aim of implementing actions for the reduction of the expected rates of change of the system. Future developments of the study should be focused in providing further validation to the applied methodologies through the comparison with involved stakeholders, in order to increase their applicability to real world systems. In the ABM a more generic rural learning system could be approached, without focusing on the specific characteristics of any particular framework, increasing its applicability to systems that share similar conditions. Moreover, different shocks could be included in the design of the model, to which the simulated agents respond e.g., shocks related to climatic conditions and environmental degradation.

References

A. K., L., & Kongolo, M. (2014). Rural Roads and Agricultural Development in Swaziland. *Journal of Social Science Studies*, *2*(1), 209. https://doi.org/10.5296/jsss.v2i1.6561

American Psychological Association (APA). (2021). https://www.apa.org/

Baggio, J., & Hillis, V. (2018). Managing ecological disturbances: Learning and the structure of social-ecological networks v1.1.0. *CoMSES Computational Model Library*. https://www.comses.net/codebases/5502/releases/1.1.0/

Bailey, K. M., McCleery, R. A., & Barnes, G. (2019). The role of capital in drought adaptation among rural communities in Eswatini. *Ecology and Society*, *24*(3), art8. https://doi.org/10.5751/ES-10981-240308

Baiphethi, M. N., & Jacobs, P. T. (2009). The contribution of subsistence farming to food security in South Africa. *Agrekon*, *48*(4), 459–482. https://doi.org/10.1080/03031853.2009.9523836

Balke, T., & Gilbert, N. (2014). How Do Agents Make Decisions? A Survey. *JASSS*, *17*. https://doi.org/10.18564/jasss.2687

Bandura, A. (1977). *Self-efficacy: Toward a Unifying Theory of Behavioral Change*.

Banson, K. E., Nguyen, N. C., Bosch, O. J. H., & Nguyen, T. V. (2015). A Systems Thinking Approach to Address the Complexity of Agribusiness for Sustainable Development in Africa: A Case Study in Ghana: Systemic Interventions for African Agriculture. *Systems Research and Behavioral Science*, *32*(6), 672–688. https://doi.org/10.1002/sres.2270

Berger, T., & Troost, C. (2014). Agent-based Modelling of Climate Adaptation and Mitigation Options in Agriculture. *Journal of Agricultural Economics*, *65*(2), 323–348. https://doi.org/10.1111/1477-9552.12045

Blair, C., Gralla, E., Wetmore, F., Goentzel, J., & Peters, M. (2021). A Systems Framework for International Development: The Data-Layered Causal Loop Diagram. *Production and Operations Management*, *n/a*(n/a). https://doi.org/10.1111/poms.13492

Blanco, F. (2017). *Cognitive bias*. https://doi.org/10.1007/978-3-319-47829-6_1244-1

Broeke, G. T., Voorn, G. V., & Ligtenberg, A. (2016). Which sensitivity analysis method should I use for my agent-based model? *Journal of Artificial Societies and Social Simulation*, *19*(1), 5. https://doi.org/10.18564/jasss.2857

Chen, Y. (2018). External shocks, agent interactions, and endogenous feedbacks—Investigating system resilience with a stylized land use model v1.0.0. *CoMSES Computational Model Library*. https://www.comses.net/codebases/831ad15f-9444-449c-bdb6-148532380251/releases/1.0.0/

Cioffi, C., Rogers, J., Schopf, P., Luke, S., Bassett, J., Hailegiorgis, A., Kennedy, W., Froncek, P., Mulkerin, M., Shaffer, M., & Wei, E. (2015). *MASON NorthLands: A Geospatial Agent-Based Model of Coupled Human-Artificial-Natural Systems in Boreal and Arctic Regions*.

Crooks, A. (2018). An Agent-Based Model of Rural Households' Adaptation to Climate Change. *Journal of Artificial Societies and Social Simulation, The*, *24*, 4. https://doi.org/10.18564/jasss.3812

Ding, Z., Gong, W., Li, S., & Wu, Z. (2018). System Dynamics versus Agent-Based Modeling: A Review of Complexity Simulation in Construction Waste Management. *Sustainability*, *10*(7), 2484. https://doi.org/10.3390/su10072484

Dlamini, B., & Keregero, K. (2002a). *Objectives Achievement of the Schools Agriculture Program in Swaziland: Implications for Future Curriculum Reforms*. https://doi.org/10.5191/JIAEE.2002.09105

Dlamini, B., & Keregero, K. (2002b). Objectives Achievement of the Schools Agriculture Program in Swaziland: Implications for Future Curriculum Reforms. *Journal of International Agricultural and Extension Education*, *9*(1). https://doi.org/10.5191/jiaee.2002.09105

Dlamini, D. V., Dlamini, S. G., Akelrele, D., & Jele, Q. (2019). The Influence of Price and Non-Price Factors on Acreage Response of Maize in Eswatini. *Journal of Agriculture and Crops*, *53*, 38–42. https://doi.org/10.32861/jac.53.38.42

Dlamini, L. N. (2019). *Determinants of commercial orientation and the level of market participation by women maize farmers in Eswatini A case study of the Highveld region*.

Dlamini, M. M., & Worth, S. (2019). Readiness of the Swaziland sugar industry towards the use of information and communication technology: Perceptions of smallholder sugarcane farmers and extension officers. *South African Journal of Agricultural Extension (SAJAE)*, *47*(3). https://doi.org/10.17159/2413-3221/2019/v47n3a518

Dlamini, N. S., Makhanya, M., Rowshon, M. K., & Sithole, S. (2014). CDAA Framework for Development of Sustainable Large-scale Smallholder Irrigation Schemes in Swaziland. *Agriculture and Agricultural Science Procedia*. http://dx.doi.org/10.1016/j.aaspro.2014.11.054

Dlamini, P. M. (1993). *Impact of organizational culture on perceived job satisfaction of mid-level social workers—ProQuest*. https://www.proquest.com/openview/368633cf4af1d1f5942686dd22d445a7/1?pq-origsite=gscholar&cbl=18750&diss=y

Dlamini, S., Dlamini, D., & Mashinini, M. (2019). *The Effects of Monetary Policy on Agricultural Output in Eswatini*. https://doi.org/10.32861/ijefr.55.94.99

Dlamini, S., Laudia, O., Vilane, F., & Fanifosi, G. (2020). *Impact of agricultural input subsidy on productivity of small-scale maize farmers in the Hhohho Region of Eswatini*. 785–794.

Dlamini-Mazibuko, B. P. (2020). *ECONOMIC ANALYSIS OF SUPERMARKETS AS A MARKETING CHANNEL CHOICE FOR FRESH PRODUCE SMALLHOLDER FARMERS IN ESWATINI*. 155.

Eseonu, C., & Egbue, O. (2014). Socio-cultural influences on technology adoption and sustainable development. *IIE Annual Conference and Expo 2014*, 2711–2716.

eSwatini. (2016a). *Swaziland drought assessment report- Rapid assessment 2015-2016 season*.

eSwatini. (2016b). *Swaziland National Climate Change Policy*.

eSwatini. (2017). *Swaziland economic conference 2017*.

eSwatini. (2018a). *ESwatini VAC- Annual Vulneraility Assessment and Analysis Report*.

eSwatini. (2018b). *ESwatini zero hunger startegic review*.

FAO. (1997). *Land tenure, governance and sustainable irrigation development*. http://www.fao.org/3/w7314e/w7314e0a.htm

FAO. (2002). *The Role of Agriculture in the Development of LDCs and their integration in the world's economy*.

FAO. (2005a). *AQUASTAT Reports. Country profile—Swaziland*.

FAO. (2005b). *Special Report Swaziland- June 2005*. http://www.fao.org/3/J5512e/J5512e00.htm

FAO. (2015a). *National Investment Profile. Water for Agriculture and Energy: Swaziland*. 48.

FAO. (2015b). The economic lives of smallholder farmers. *The Economic Lives of Smallholder Farmers An Analysis Based on Household Data from Nine Countries*, 48.

FAO. (2018). *Swaziland looks to a revitalized agriculture sector*. Food and Agriculture Organization of the United Nations. http://www.fao.org/in-action/swaziland-looks-to-a-revitalized-agriculture-sector/en/

FAO. (2019). *Support to the incorporation of climate Smart agriculture in swaziland schools and Agriculture training centres programmes*.

Food and Agriculture Organization of the United Nations (Ed.). (2017). *The future of food and agriculture: Trends and challenges*. Food and Agriculture Organization of the United Nations.

Forrester, J. W. (1999). *System Dynamics: The Foundation Under Systems Thinking*.

Grimm, V., Polhill, G., & Touza, J. (2013). *Documenting Social Simulation Models: The ODD Protocol as a Standard | SpringerLink*. https://link.springer.com/chapter/10.1007/978-3-540-93813-2_7

Haraldsson, H. (2004). *Introduction to system thinking and causal loop diagrams*.

Heppenstall, A., Crooks, A., See, L. M., & Batty, M. (Eds.). (2012). *Agent-Based Models of Geographical Systems*. Springer Netherlands. https://doi.org/10.1007/978-90-481-8927-4

Hulme, A., Mclean, S., Salmon, P., Thompson, J., Lane, B., & Nielsen, R. (2018). Computational methods to model complex systems in sports injury research: Agent-Based Modelling (ABM) and Systems Dynamics (SD) modelling. *British Journal of Sports Medicine, 53*. https://doi.org/10.1136/bjsports-2018-100098

IFAD. (2012). *Sustainable smallholder agriculture: Feeding the world, protecting the planet*.

Jager, W., Janssen, M., & Viek, C. (2001). Experimentation with household dynamics: The consumat approach. *International Journal of Sustainable Development*, *4*, 90–100. https://doi.org/10.1504/IJSD.2001.001548

Kangogo, D., Dentoni, D., & Bijman, J. (2020). Determinants of Farm Resilience to Climate Change: The Role of Farmer Entrepreneurship and Value Chain Collaborations. *Sustainability*, *12*(3), 868. https://doi.org/10.3390/su12030868

Kemper, T. D. (2006). Power and Status and the Power-Status Theory of Emotions. In J. E. Stets & J. H. Turner (Eds.), *Handbook of the Sociology of Emotions* (pp. 87–113). Springer US. https://doi.org/10.1007/978-0-387-30715-2_5

Kremmydas, D., Athanasiadis, I. N., & Rozakis, S. (2018). A review of Agent Based Modeling for agricultural policy evaluation. *Agricultural Systems*, *164*, 95–106. https://doi.org/10.1016/j.agsy.2018.03.010

Kunene, M. N. (2019). PERCEPTIONS OF SMALL-SCALE MAIZE FARMERS ON CLIMATE CHANGE IMPACTS IN HHOHHO, MANZINI AND SHISELWENI REGIONS OF THE KINGDOM OF ESWATINI. *Applied Ecology and Environmental Research*, *17*(4). https://doi.org/10.15666/aeer/1704_73457356

Kwa, A. (2001). *Agriculture in Developing Countries: Which Way Forward?* https://www.iatp.org/sites/default/files/Agriculture_in_Developing_Countries_Which_Way_.htm

Mabaso, S., Singwane, S., van Zuydam, I., Nhlengetfwa, B., & Mamba, S. (2020). *Assessment of Socio-economic Impacts of the Climate Smart Gardens Project in Low Income Residential Areas in Mbabane City, Eswatini*.

Mabuza, M. L., Ortmann, G. F., Wale, E., & Mutenje, M. J. (2016). The effect of major income sources on rural household food (in)security: Evidence from Swaziland and implications for policy. *Ecology of Food and Nutrition*, *55*(2), 209–230. https://doi.org/10.1080/03670244.2015.1121482

Manyatsi, A. M., & Singwane, S. S. (2019). *Land Governance in eSwatini*. 41.

Masuku, M. (2011). Determinants of Sugarcane Profitability: The Case of Smallholder Cane Growers in Swaziland. *Asian Journal of Agricultural Sciences*, *3*.

Mhlanga-Ndlovu, B. F. N., & Nhamo, G. (2017). An assessment of Swaziland sugarcane farmer associations' vulnerability to climate change. *Journal of Integrative Environmental Sciences*, *14*(1), 39–57. https://doi.org/10.1080/1943815X.2017.1335329

Mijinyawa, Y., & Dlamini, S. S. (2008). *Impact assessment of water scarcity at Somntongo in the lowveld region of Swaziland*. http://ir.library.ui.edu.ng/handle/123456789/1655

Mlenga, D., & Maseko, S. (2015). Factors Influencing Adoption of Conservation Agriculture: A Case for Increasing Resilience to Climate Change and Variability in Swaziland. *Journal of Earth and Environmental Science*, *5*, 11–15.

MOA. (2016). *Swaziland Market Assessment Report*.

Ndulo, M. B., & Assié-Lumumba, N. T. (2020). *Education and Development: Outcomes for Equality and Governance in Africa*. Springer Nature.

Nguyen, N., & Bosch, O. (2014). The Art of Interconnected Thinking: Starting with the Young. *Challenges*, *5*. https://doi.org/10.3390/challe5020239

Njeim, N. (2018). Socioeconomic Impacts of Infrastructure Investment in Eswatini: The Case of LUSIP. *Graduate Theses and Dissertations*. https://scholarworks.uark.edu/etd/2944

Nowak, S. A., Matthews, L. J., & Parker, A. M. (2017). *A General Agent-Based Model of Social Learning | RAND*. https://www.rand.org/pubs/periodicals/health-quarterly/issues/v7/n1/10.html

Nyanga, P. H. (Ed.). (2012). Factors Influencing Adoption and Area under Conservation Agriculture: A Mixed Methods Approach. *Sustainable Agriculture Research*. https://doi.org/10.22004/ag.econ.231353

Parry, M., Canziani, O., Palutikof, J., van der Linden, P., & Hanson, C. (2007). Climate Change 2007: Impacts, Adaptation and Vulnerability. In *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.

Peter, G. (2011). *The impact of small scale irrigation schemes on household food security in Swaziland*. 16.

P.H. Thangata & J.R.R. Alavalapati. (2003). *Agroforestry adoption in southern Malawi: The case of mixed intercropping of Gliricidia sepium and maize—ScienceDirect*. https://www.sciencedirect.com/science/article/abs/pii/S0308521X03000325

Rogers, E. M. (1995). *Diffusion of innovations*. Free Press.

Rugube, L. M., Nsibande, S. P., Masarirambi, M. T., & Musi, P. J. (2019). Factors Affecting Profitability of Smallholder Vegetable Farmers in the Shiselweni Region, Kingdom of Eswatini (Swaziland). *Sustainable Agriculture Research*, *8*(1), 104. https://doi.org/10.5539/sar.v8n1p104

Sacolo, T., Mohammed, M., & Dlamini, T. (2018). Evolution of trade in Eswatini from 1968 to 2015: A developmental perspective. *African Review of Economics and Finance*, *10*(2), 151–168.

Sallinger-McBride, J., & Picard, L. A. (1989). Rural Development Areas in Swaziland: The Politics of Integrated Rural Development. *Comparative Politics*, *22*(1), 1. https://doi.org/10.2307/422319

Schulze, J., Müller, B., Groeneveld, J., & Grimm, V. (2017). Agent-Based Modelling of Social-Ecological Systems: Achievements, Challenges, and a Way Forward. *Journal of Artificial Societies and Social Simulation*, *20*(2), 8.

Sherwood, D. (2011). Seeing the Forest for the Trees: A Manager's Guide to Applying Systems Thinking. *Undefined*. https://www.semanticscholar.org/paper/Seeing-the-Forest-for-the-Trees%3A-A-Manager%27s-Guide-Sherwood/38f56190694a9fca7e853fa18f37d470ff18eabd

Simelane, S. M., Terblanche, S. E., & Masarirambi, M. T. (2019). Collective Action For Access To Inputs, Finance, Markets And Extension For Smallholder Farmers In Eswatini. *South African Journal of Agricultural Extension (SAJAE)*, *47*(2). https://doi.org/10.17159/2413-3221/2019/v47n2a500

Sukati, M. A. (2013). *Measuring Maize Price Volatility in Swaziland using ARCH/GARCH approach*. 19.

Tfwala, C. M., Mengistu, A. G., Seyama, E., Mosia, M. S., van Rensburg, L. D., Mvubu, B., Mbingo, M., & Dlamini, P. (2020). Nationwide temporal variability of droughts in the Kingdom of Eswatini: 1981–2018. *Heliyon*, *6*(12), e05707. https://doi.org/10.1016/j.heliyon.2020.e05707

Tisue, S., & Wilensky, U. (2004). *NetLogo: A Simple Environment for Modeling Complexity*. 10.

Turner, B. (1994). Small-scale irrigation in developing countries. *Land Use Policy*, *11*(4), 251–261. https://doi.org/10.1016/0264-8377(94)90051-5

Uduji, J. I., Okolo-Obasi, E. N., & Asongu, S. A. (2018). The impact of e-wallet on informal farm entrepreneurship development in rural Nigeria. *The Electronic Journal of Information Systems in Developing Countries*, e12066. https://doi.org/10.1002/isd2.12066

UN. (2017). *Country profile Swaziland 2016*. https://repository.uneca.org/handle/10855/23674

Vennix, J. A. M., Akkermans, H. A., & Rouwette, E. A. J. A. (1996). Group model-building to facilitate organizational change: An exploratory study. *System Dynamics Review*, *12*(1), 39–58. https://doi.org/10.1002/(SICI)1099-1727(199621)12:1<39::AID-SDR94>3.0.CO;2-K

WFP. (2021). *Eswatini | World Food Programme*. https://www.wfp.org/countries/eswatini

World Bank. (2010). *The Education System in Swaziland: Training and Skills Development for Shared Growth and Competitiveness*. The World Bank. https://doi.org/10.1596/978-0-8213-8324-7

World Bank Group. (2020). *eSwatini Systematic Country Diagnostic- Toward Equal Opportunity: Accelerating Inclusion and Poverty Reduction*.

Worldbank. (2011). *Swaziland—Priorities for the development of smallholder agriculture in Swaziland (English)* [Text/HTML]. World Bank. https://documents.worldbank.org/en/publication/documents-reports/documentdetail

Xaba, B., & Masuku, M. (2012). Factors Affecting the Choice of Marketing Channel by Vegetable Farmers in Swaziland. *Sustainable Agriculture Research*, *2*. https://doi.org/10.5539/sar.v2n1p112

Zheng, C., Liu, Y., Bluemling, B., Chen, J., & Mol, A. P. J. (2013). Modeling the environmental behavior and performance of livestock farmers in China: An ABM approach. *Agricultural Systems*, *122*, 60–72. https://doi.org/10.1016/j.agsy.2013.08.005

Appendix 1.

Variables and links in the CLD

1) SNL subsistence production
2) Water use
3) Water availability
4) Climate change
5) Precipitation variability
6) Rural water infrastructures development
7) SNL cash crop production
8) Private irrigation systems
9) TDL Cash crop production for export
10) Availability of funds for investments
11) Import of basic goods
12) Farmers access to market as consumers
13) Farmers competitiveness on price
14) Farmers access to market as traders
15) income from agriculture
16) Access to education and training
17) Farming techniques and resource management
18) Commercial skills
19) Availability of production subsidies
20) Cost of inputs
21) Access to input, tools and machinery
22) Crop yield
23) Access to financial credit
24) Land policy
25) Access to information and technology
26) Investment in road and transportation infrastructure
27) Schooling and extension training Structure
28) Institutional agreement, legal framework & good governance

Linked variables	Link type	Explanation
V4- V5 Climate Changes / Precipitation variability	L+	Climate changes in the country is mainly evident in changing precipitation - including variability, persistent drought and heightened storm intensity, which negatively affects agricultural yields, biodiversity, forests and the availability of clean water (eSwatini, 2016b); with droughts representing a major threat to resource dependent livelihoods *(Bailey et al., 2019)*. According to (Tfwala et al., 2020) droughts have increased in prevalence and severity after the year 2000, especially in the dry Lowveld. The frequency of droughts is higher in the dry areas of the country compared to the high rainfall areas. The results highlighted that droughts are generally increasing in the country. In the Kingdom of Eswatini the occurrence of drought in the past has resulted in serious adverse effects, especially in the agricultural sector. For instance, the 2015/16 season was dry across the country and sugarcane, which is termed "Swazi gold", suffered a 30% reduction in revenue.
V5- V3 Precipitation variability /Water availability	L-	Communities in low and middle-income countries are heavily dependent on natural resources, which makes them especially vulnerable to impacts of climate change (Parry et al., 2007). In Swaziland, like in many other developing countries, the agricultural sector is highly dependent on rain-fed production and therefore vulnerable to weather shocks. Maize is the primary staple crop and is widely grown by smallholder farmers throughout the country, with a dual sorghum-maize regime found in the Lowveld region and fewer parts of the Middleveld of Swaziland. Among the smallholder farmers almost all production is rain-fed with very few farmers using mechanized irrigation. Climate change therefore has significantly reduced agricultural production and exacerbated poverty and food insecurity in the kingdom (Mamba, 2016). Spatial and temporal changes in precipitation and temperature patterns have major impacts on the viability of both dryland and irrigated farming. Sugarcane production in Swaziland is strictly dependent on the availability of water for irrigation, in fact water is a limiting factor in sugarcane production. The impacts of climate change on both resource availability (for irrigation abstraction) and water demand (for crop production) are investigated in literature (Knox, 2010) and highlight the impact of high temperatures and rainfall variability as two major threats for Sugarcane crop production. During the 2015/2016 drought, persistent severe water shortages occurred both in rural and urban areas (affecting many of the 300,000 people facing food shortages) and caused the Government to ration water and many communities to rely on external water supply support. The drought had long-term impacts on ground water supply (of which 78 percent of the rural population depends on) due to the poor recharge of aquifers (World Bank, 2019).
V2- V3 Water use /Water availability	L-	The surface water resources of eSwatini are estimated at 4.5 km3/year with 42 percent originating from South Africa. The five main river systems in the country are the Komati, the Lomati, the Mbuluzi, the Usutu and the Ngwavuma. The Komati and the Lomati river systems are found in the north of the country and both originate in South Africa and flow out of eSwatini back into South Africa before entering Mozambique. Sources of water vary in rural areas, with tap water making up 44 percent of rural supply, groundwater 31.5 percent and surface water up to 21 percent (World Bank, 2019). The discharges from these sources often are low and get dried during the dry season. During this season, the inhabitants who have the means reach long distances from the community to find available resources. The country recognizes the need for sustainable development and efficient use of its scarce water resources to support economic growth, diversification and poverty eradication. Therefore, over the past decade the eSwatini government has commissioned the construction of various infrastructures to provide water throughout the country, both for agriculture and for domestic use (GovSw, 2018).
V3-V1	L+	In Eswatini, smallholder farmers are found mainly on SNL where they practise mixed farming which involves growing crops and rearing livestock. Smallholder farmers are those farmers that produce crops and raise livestock on a small piece of land while using available resources which exclude expensive modern technology and machinery

Water availability / Small- scale food production		(Rugube et al., 2019). Water scarcity inflicts injuries on the social and economic lives of the populace. The spatial distribution of water is uneven throughout the country; water sources are often not located where there is demand, so it requires tanks and conveyor systems to carry the water, hence the need for storage. Sources of water available in many areas of eSwatini are related to natural basins, boreholes and rivers. The discharges from these sources often are low and get dried during the dry season. During this season, the inhabitants who have the means reach long distances from the community to find available resources. Rain water harvesting as a source of water have very little impact in some areas of the country which leads small holders to use water mainly for domestic and livestock and no irrigation activities. In many areas of the country, irrigation is not practiced due to the lack of water sources in nearby areas (Mijinyawa & Dlamini, 2008).In the last two decades, the country has developed two main irrigation projects in an effort to reduce poverty and increase investment into pro-poor infrastructure projects to help rural households produce their way out of poverty through the commercialisation and intensification of irrigated agriculture (Njeim, 2018). Although, the National Development Strategy (NDS) aim is to involve small-scale farmers in the expansion of the sugar industry in the region (as the most important segment of the agricultural export sector) by supporting small farmers in the transition from an agricultural system of subsistence to the production of income crops.
V1- V2 SNL subsistence production / Water use	L+	The failure or loss of crop production due to pests and drought is a common factor for small holder farmers. The majority (92%) of community groups in Swaziland perceive water supply as a problem, and as such access to water on SNL for small holders is seen as fundamental for them to use their land resources to improve food security. The irrigation sector uses approximately 96 percent of water in Swaziland. Within the irrigation sector, over 90 percent of the water is used by the sugar industry (Peter, 2011). The construction of dams and infrastructures for the irrigation of rural areas has represented an element of importance for national development in the last 2 decades. In particular, two projects have been implemented whose objective is the supply of water in the rural and drought areas of Swaziland in order to guarantee a continuous supply and standard of living of the smallholder farmers by the commercialization and intensification of irrigated agriculture of sugarcane through a gradual withdrawal from the subsistence farming of maize predominately practiced in the region. In a study by (Peter, 2011) respondents were using the irrigation water system mainly for irrigating sugar cane grown on cooperative basis. Crop production on individual household plots continued to suffer crop losses due to drought.
V3- V7 Water availability /SNL cash crop production for export	L+	The objectives of the LUSIP National Irrigation Program aim to increase the efficiency of sugarcane value chains by integrating smallholder farmers into the commercial economy through the creation of farmer-run irrigation companies, while improving people's quality of life living within the PDA (Project Development Area) (Njeim, 2018). In an article by (N. S. Dlamini et al., 2014), the authors highlight how the development of small-scale irrigation systems in the southern African region has had significant investments in recent years to extend the participation of smallholder farmers in the sugar industry, expanding within the region. In Swaziland, smallholder irrigation programs have been established with government help to increase smallholder incomes by integrating them into the existing commercial market-oriented environment. Despite national efforts to provide assistance to small farmers through extension services and sector specialists, small farmers lack training and marketing-oriented knowledge (Masuku, 2011).
V7- V2 SNL cash crop production for export / Water use		In the Swaziland sugar industry sustainability of the small-scale sugarcane farms is key for the sustainability of the overall sugar industry. This is mainly due to the fact that the expansion of the sugar industry over the last 10 years is mostly attributed to the entry of smallholder sugarcane growers. To guide the formulation of development plans in the Country, the National Development Strategy (NDS) identified a set of priorities, including the shift of smallholder farmers from rain-fed subsistence farming

		to irrigation-based commercial agricultural production. Two major water irrigation projects (KDDP and LUSIP) have been implemented since 1999, in one of the driest and poorest areas of the country (the Lowveld). The aim of these projects is to provide irrigation to 18 500 ha of land, leading local smallholder farmers to shift from a subsistence agricultural system to cash-crop production, mainly sugarcane (N. S. Dlamini et al., 2014).
V9- V2 TDL cash crop production for export /Water use	L-	Agriculture in Eswatini is split between largely rain-fueled subsistence production by smallholder farmers in SNL (Swazi National Lands), which are real lands distributed to the population by local Chefs, in which predominantly maize and vegetable-fueled vegetables are grown representing 90% of the total of small owners; and Title Deed Lands (TDL), cash crops with irrigation available on large private estates (Worldbank, 2011). Sugar production in Swaziland is not possible without irrigation. As a result, most of the water used for agriculture (96%) in Swaziland is used for sugar cane production (N. S. Dlamini et al., 2014). 91% of the irrigated land in eSwatini is under the control of large domestic or expatriate companies and used for the production of export goods such as sugarcane and cotton, which account for more than 60% of the country's total agricultural production (Njeim, 2018) and 24% of national merchandise exports in 2019 (World Bank Group, 2020); limiting the availability of water in the country and affecting small-scale food agricultural production.
V8- V9 Private irrigation systems /TDL cash crop production for export		Public and private largescale schemes usually extract the irrigation water from reservoirs; while in small scale private schemes, irrigation water is normally abstracted from the rivers using electric pumps (FAO, 2015a). In 2005 about 10 large irrigation schemes (> 500 hectares) occupy 67 percent of the irrigated land. Medium irrigation schemes (50-500 hectares) and small irrigation schemes (< 50 ha) occupy 20 percent and 13 percent of the land respectively. Large schemes are dominant in TDL, while small schemes are dominant in SNL (FAO, 2005a).
V6- V7 Rural water infrastructures development/ SNL cash crop production	L+	In 2007, the SNAS (Swaziland National Agricultural Summit) identified the absence of a comprehensive water resources development program (Policy) as one of eleven key constraints for planning the reorientation of agricultural production systems to enable farmers to create wealth for themselves. The government of Swaziland has developed two main irrigation programs in the country: the Komati Downstream Development Project (KDDP) and the Lower Usuthu Smallholder Irrigation Project (LUSIP). The main objective of the KDDP is to assist farms in the project development area (PDA) to establish and manage irrigated farms covering 6,000 hectares. A total of 5,206 hectares have been developed to date. 4,616 hectares are planted with sugar cane. 590 hectares are used for the production of other crops. LUSIP aims to benefit 4,600 families (34,000 people) by transforming subsistence farmers into commercial farmers of irrigated land producing money and food crops (Njeim, 2018). As reported by (Dlamini et al., 2014) in less than ten years the LUSIP irrigation program has achieved the following; better equal access to water and land for more than 15,000 rural residents in what used to be the poorest part of the country (Lowveld); it was built in six chiefdoms with an area of 3,370 hectares under irrigation; it benefited about 20,479 people from the community of the project area; increased median household income to $ 121.8 per month; and 2029 households have access to clean water supplies. A phase II of the LUSIP irrigation project is being implemented.
V1- V11 SNL subsistence production/ Import of basic goods	L-	The large number of people in eSwatini depend on the rural economy, which is dependent on rain-fed agriculture. Although smallholder producers constitute 70% of the population and occupy 75% of the crop land, yet contribute a meagre 11% of total agricultural outputs in the country, with average cereal yields as low as 1.1 tonne/hectare which makes eSwatini a food deficit country. Food production deficits

		can lead to substantial increases in imports to meet local food needs, which can result in a widened trade balance for the importing country (Sacolo et al., 2018). The country is a net importer of maize and satisfies its supply deficit almost entirely with maize grain from South Africa. Maize remains the important staple food crop grown on Swazi Nation Land for subsistence purposes and food security (MOA, 2016). It is also the measure of food security in the country (FAO, 2005b). However, though a substantial number of rural households produce it, the country has never produced enough maize for total domestic consumption. Eswatini only produces enough to meet about 45% (110,250 tonnes) of its annual total cereal requirements of 245,000 tonnes. During the 2015/16 drought, maize production dropped by 67% forcing the country to import 30,446 tonnes of maize from South Africa. These production statistics indicate that the country is food insecure and, since the early 1990s, has shifted from being a net exporter of food to depending on food aid to feed its population (Sacolo et al., 2018).
V11 - V12 Import of basic goods /Farmers access to market as consumers	L-	The continued increase in maize imports and slump in local production in recent years means the country is more exposed to global developments in maize markets and is becoming a price taker. Price volatility in a stable food like maize is particularly important for Swaziland in that most Swazi are poor. It is known that poor segments of society spend most of their income on food. This means that unpredictable spikes in stable food prices that form major caloric intake become an important food security issue especially for poor countries. Unpredictable weather patterns and climate change result in unpredictable price movements in agricultural commodities because they cause supply disruptions (Sukati, 2013) Food production deficits can lead to substantial increases in imports to meet local food needs, which can result in a widened trade balance for the importing country (Sacolo et al., 2018). The country is a net importer of maize and satisfies its supply deficit almost entirely with maize grain from South Africa , where a reduced harvest and higher international prices have driven up prices, consequently inflating import costs for Eswatini. On June 2019, the domestic price of white maize was increased for a period of three months. The selling price was set at SZL 4 000 (USD 283) per tonne while the buying price at SZL 2 800 (USD 198) per tonne, about 15 percent and 8 percent, respectively, higher than the previous year's levels (FAO, Food Price Moitoring and Analysis, 2019). The hunger situation in the country is exacerbated by high rates of poverty at about 59 percent and income inequality with a Gini Coefficient of 49.39 (S. Dlamini et al., 2019). Moreover, high unemployment rates at 28 percent further reduces the capacity of the economically active population to provide adequate food for dependents, considering high annual food import bill of over USD 300 million. In order for households to meet their food and nutrition requirements, they start relying on food donations from the Government, private sector and development partners (eSwatini, 2018b).
V15- V12 Income from agriculture /Farmers access to market as consumers	L-	Accessibility to food by the vulnerable and poor due to low purchasing power is the main problem. The country's National Development Strategy (NDS) and PRSAP recognise that Eswatini has a large rural population that suffers from inadequate access to food and high unemployment. Natural shocks so as social and economic barriers heighten vulnerability to food insecurity because a majority of the population in Eswatini depend on the rural economy, which is dependent on rain-fed agriculture. Given the continued unreliable weather pattern throughout the world, coupled with escalating poverty levels, rural households in developing countries have become more vulnerable to food-related shocks limiting its availability and access (Mohammed and Dlamini, 2018). The Comprehensive Agriculture Sector Policy (CASP) (2005) acknowledges the fact that

		the deteriorating food security and poverty dynamics in the country can largely be explained by the poor performance of the agriculture sector. Households' access to food is strongly dependent on its occupation status since a large proportion of the food consumed is purchased (Banele Nhlengethwa, & S.S. Nhlengethwa, 2020) and the majority of the rural people depend on cash income for survival strategies. As a result, some households have resorted to maintaining a diversified portfolio of income sources, with those outside agriculture constituting a major component (Mabuza et al., 2016). According to the data reported by the Swazi Gov (SwGov, 2016), major livelihood activities for rural households in eSwatini are: formal labour (18%); Remittances (17%); and small business (14%); Food crop production (12%); Social grants (11%) and casual labour (11%). Moreover, the official unemployment rate in eSwatini is 28.2 percent (Swaziland, 2007), the actual figure is estimated at 40 percent, even higher in rural areas, with young people and women being the adversely affected groups (Absalom M. Manyatsi, 2013). The labour force participation in the country is still one of the lowest in Africa (51.3 per cent) and most of the jobs remain informal, with low-productivity and low-skills development (UN, 2017). Out of about 1.1 million1 people, 63% were poor in 2010 while approximately 89% of all rural households were living in abject poverty during the same period. The Swaziland Household Income and Expenditure Survey of 2010 indicates that one in two people in rural areas were also food poor (eSwatini, 2017). Low productivity and low income from agriculture affect farmers capacity to meet their food requirements through self- production or the purchase of imported food which is linked to the variability of market prices.
V11- V32 Import of basic goods /Farmer's competitiveness on price		In general, average productivity in Swaziland is significantly lower than in South Africa. All inputs for production (hybrid seeds, fertilizers, pesticides, etc.) are imported from South Africa. They are significantly more costly in Swaziland than in SA thereby raising production costs of Swazi farmers. This partly explains why Swazi maize/products is/are comparatively more expensive. The situation is compounded by persistent unfavourable climatic conditions; the country has experienced successive droughts and erratic rains (PDPE, SENAC, ODJ, 2006) and small-scale farmers do not have the structure or the knowledge to face this common shocks. This greatly discourages the remaining farmers from producing grain or vegetables for commercial purposes as it becomes difficult to compete with the imported vegetables (Rugube et al., 2019).
V13 - V14 Farmers competitiveness on price / Farmer's access to market as traders		Farmers in Swaziland, and especially smallholders, face enormous challenges finding markets for their production. Local markets are frequently flooded with low-price imported products, which sometimes enter the country without any quality control. Institutions that have been established to support farmers in the marketing of their produce, such as the National Agriculture Marketing Board (NAMBoard), the National Maize Corporation (NMC), the Swaziland Dairy Development Board (SDDB), and the Swaziland Cotton Board (SCB), reach relatively limited numbers of clients. Moreover, the high cost of inputs and implements is compounded for poorer farmers by the lack of access to short-term production credit needed to finance inputs, especially fertilizer. Finally, as a land-locked country, Swaziland depends on goods being trucked long distances, making it particularly vulnerable to increases in fuel prices. Subsistence-oriented farmers on SNL are particularly vulnerable to increases in transport costs, as they cannot pass on increases in energy costs to end users. In Swaziland maize is imported through the state-owned National Maize Corporation established in 1985. NMC was established with the objectives of guaranteeing market to local maize producers at competitive prices while at the same time providing good quality maize to Swazi consumers at affordable prices (i.e., protect farmers and at the

		same time stabilise markets). In the country, small scale maize producers have the choice to sell to whoever offers the best price among NMC, private grain traders or the millers. Although National efforts to include small holder farmers into local markets, low prices of imported goods remain a limit for small-scale commercialization due to the high cost of inputs prevailing in the country and the risks related to common drought events in the area. The market is such that the costs for small farmers to use the high input system are larger than for big farmers. Poor farmers cannot afford to buy fertilizer and inputs in volume. Big growers get discounts for large purchases. Poor farmers cannot hold out for the best price for their crops, while larger farmers whose circumstances are less desperate can. Big farmers can afford to pay for irrigation services, which may not be within reach of small farmers. This reduces their incentive to participate in economic transactions and result in subsistence rather than market-oriented production systems as a result farmers selling their produce directly to final consumers and private traders at rural or urban markets, as opposed to abiding by their contracts with NAMBoard (Xaba & Masuku, 2012).
V26 - V14 Investments in roads and transportation infrastructures /Farmers access to market as traders		Physical barriers such as infrastructure development; transaction costs, access to information and a lack of goods affect market access for rural households. Several studies show that family-owned endowments of resources are key drivers of commercialization. Productive resources facilitate engagement in economic activities and lead to greater agricultural productivity. Household assets include land, livestock, communication devices and means of transportation (Dlamini-Mazibuko, 2020). Rural roads are fundamental in supporting both rural and agricultural development to improve the socio-economic conditions of people, in order to facilitate the distribution of agricultural products and its accessibility to the population. Rural roads play a role in providing physical access. In fact, the agricultural production of the small farmers of Swaziland has as its final destination the main centers of the country, where it is distributed to the various local markets. About 3/4 of the rural roads in the study conducted by (A. K. & Kongolo, 2014) in eSwatini are in poor condition and need to be repaired. The lack of adequate rural infrastructure in the country has dramatically affected food production and distribution. This in turn can create food shortages in major centers, where food demand is very high. The study reports that the main factors limiting food supply include the extreme state of the roads linking to the main traders and farmers centers, as well as the cost of fuel. Another dominant problem in most of Africa's rural areas is the lack of cheap transportation. Evidence shows that even in places where there are roads with poor access to bus, taxi or matatu systems, people still have to travel long distances to access such vehicles as the systems are often not sufficiently developed. Walking is the most important form of non-motorized transportation. Other forms of non-motorized include bicycle, human porterage, wheelbarrow and animal-drawn cart. Rural road coverage is poor and physical markets are rare, meaning farmers often have to travel long distances to sell their produce (Worldbank, 2011)
V25- V11 Access to information and technology /Farmer's	L+	(Hobbs, 1997) identified various types of Transitional Costs in the marketing of agricultural products. These include information costs associated with searching for markets and trading partners. The majority of farmers are in remote rural areas that are far from towns and consumers. This leads to high search and transport costs. In

access to market as traders		addition, once the consumer has been identified, negotiation and bargaining costs erupt because of information asymmetries concerning market prices, more monitoring and enforcement costs, as farmers need to ensure that parties meet the terms of exchange. These costs explain why some farmers engage in output markets while others do not (Dlamini-Mazibuko, 2020). The use of information and communication technologies (ICT), in particular mobile phones, plays an important role in assisting Extension Services in transferring up-to-date information to farmers and in reporting farmers' needs to research centers. This process reduces travel costs by removing physical distances (M. M. Dlamini & Worth, 2019). Cell phones have a huge potential to revolutionise the way information knowledge and new technology is managed, developed and delivered to farmers. Small holder farmers need assistance from intermediaries to adopt knowledge and information. In that regard, extension officers are suggested to be the effective intermediaries for delivering information and knowledge to famers. Farmers with access to information have the ability to make informed decisions concerning production and marketing matters. Farmers would know the crop to grow (demand) and the market to supply. Mobile phones enable farmers to communicate easily with buyers and input suppliers and to access marketing information such as price (Dlamini-Mazibuko, 2020)
V14- V15 Farmers access to market as traders / income from agriculture	L+	Agricultural commercialization refers to a shift from production for consumption to market-oriented production that ensures the sale of produce. This not only increases the market share of agricultural output but also leads to higher productivity, quality, and specialization of labour. Market participation can lead to reduced food prices due to increased market competition, which lowers food processing and market costs. This improves the overall welfare of Swazi farmers by increasing their purchasing power for food as well as re-allocating limited household income (S. Dlamini et al., 2019). Lack of bargaining power along with various credit bound relationships with the buyers has led to farmers being exploited during the transaction where most of the farmers become price takers. The majority of the farmers are smallholders and hence, unable to obtain a fair price for their produce. This results to farmers not being able to sustain their livelihood (Xaba & Masuku, 2012)
V15 - V16 income from agriculture /Access to education and extension training	L+	Free Primary School education in provided since 2005 in the country, which slowly led to a slightly improvement in primary school enrolment. In the case in households involved in subsistence activities, when children are somewhat older, the opportunity cost of their being at school rather than being active in the household to assist with agricultural activities or household chores becomes a greater issue for some parents. If in addition education also becomes costly at secondary school level, it makes further education less attractive (B. Dlamini & Keregero, 2002b) The current system reproduces and cements current social inequalities. People of high SES (Socio-economic Status) have a better chance of access to quality Education, Training and Skills Development (ETSD). They have better ECCD (Early Childhood Care and Development) and General Education and Training (GET) services, better access to TVETSD (Technical and Vocational Education and Training and Skills Development), and they dominate participation in Higher Education. Rural dwellers have limited access to ETSD. Children of urban and more affluent Families have better access to virtually all levels of the ETSDS but more so for ECCD and HE (World Bank, 2010).
V27 - V16 Schooling and extension training Structure /	L-	Swaziland’s education system evolved from a traditional culturally based education. The colonial education system, as employed by the British colonial reign, segregated education standards and the local inhabitants did not receive a proper education. With the adoption of the new Swazi constitution in 2005, government committed itself to providing free primary education (FPE) to all children of school-going age . This

Access to education and training		policy was to be implemented from 2009, with the ultimate goal of all children of school-going age being enrolled by 2015. However, implementation of the FPE goal was slow. FPE has succeeded in increasing access to education for all children, especially those who had previously been prevented from attending school due to prohibitive school fees. Enrolment in primary school has steadily increased since the introduction of FPE. At secondary school level education becomes costly it which makes education less attractive (B. Dlamini & Keregero, 2002b). All formal Technical and Vocational Education and Training and Skills Development (TVETSD) institutions are in urban centres and this gives urban dwellers easier access than their rural counterparts. UNISWA's campuses are also mostly in urban and/or peri urban centers. The nonformal second chance opportunities for General Education and Training (GET) cater mainly to urban dwellers by virtue of their location. Rural dwellers tend to have access to lower levels of TVETSD. This situation does not bode well for the efforts to bridge income and social inequalities between urban and rural areas. Adult learners have limited pathways to GET, to upgrade their skills, and to retool themselves for emerging opportunities. Adults may not use the nonformal pathway to attain a primary school certificate. Without this certificate, it is difficult for them to progress through the GET levels (World Bank, 2010). On the other side, MoA (Ministry Of Agriculture) Extension Services which role would be to support farmers in agricultural development and welfare increase are no longer effective and need to be reviewed with respect to their structure, methodology, and approach. Extention Officers are often low qualified, provide inconsistent technical advice to farmers since are not equipped to provide up-to-date information about existing technologies, and they do not have the capacity to involve farmers in adaptive trials of promising new technologies (World Bank, 2010).
V17- V12 Wage employment income /income from agriculture	L+	Some households have resorted to maintaining a diversified portfolio of income sources, with those outside agriculture being an important component (Mabuza et al., 2016). Indeed, households' access to food depends on their employment status as a large percentage of the food consumed is purchased (Mabaso et al., 2020) and most rural people depend on income in cash for survival strategies. The agricultural sector (both subsistence and commercial) employs about 70% of the workforce. However, agriculture's contribution to GDP is less than 10% because the economy has shifted to coal, pulp, sugar, beverage concentrates, textiles and clothing, and other manufacturing products (Manyatsi & Singwane, 2019). According to data reported by the Swazi Gov (eSwatini, 2019), the main livelihood activities for rural families in eSwatini are: formal work (18%); Remittances (17%); and small businesses (14%); Production of food crops (12%); Social contributions (11%) and occasional work (11%). As reported in (Mabuza et al., 2016) about 9% relied on production in a company while 46%, 24 % and 20%, respectively, relied on off-farm economic activities, remittances, and non-agricultural economic activities for food and income. The same study defines that 38% of respondents relied primarily on income generated outside the company, although the forms of wage employment opportunities available in rural areas are likely to be less profitable and do not require specialized qualifications. Under these circumstances, people with advanced formal training migrate to urban areas in search of better-income jobs, which will enable them to support their rural families through remittances. The official unemployment rate in eSwatini is 28.2% (Swaziland, 2007).
V16 - V18		A deep understanding of training and educational role in agricultural development has been given in the last decades. Dlamini et al. (1993) highlights the role of training as an essential resource input for all contributors to the process of technological change

Access to education and training / Commercial skills		and agricultural growth, which is also required for both scientific and technical staff in the research and extension services. Training involves both formal and non-formal forms and must be a continuing activity within a national research and extension system. Agricultural training at different institutions is provided for various purposes. At school level, the aim is to change peoples' attitude. There is also a need for post-graduate programmes to produce manpower to conduct agricultural research. Problems hampering the attainment of food security are associated with a lack of a national manpower plan, financial resources, coordination and cooperation among institutions and curriculum content relevance. Marketing plays a critical role in meeting the overall goals of food security, poverty alleviation and sustainable agriculture, particularly among smallholder farmers in developing countries like Swaziland (Xaba & Masuku, 2012). Masuku 2011 highlights issues in commercialisation for Sugarcane producers in Swaziland stating a smallholder farmer need to be trained and motivated in order to be commercially oriented. The Swaziland Government should play a role in providing smallholder growers with some training in business management skills and in addressing issues of concern to farmers as they develop in order to improve their yields. This should be done through the government extension agents, provided specifically to assist smallholder (sugarcane) farmers, and the various government departments involved in providing training in business and management skills (Masuku, 2011). Should be considered that sugarcane farmers are supported by the government due to national interests on production; on the other side, small scale food producers are pushed to a transition from food production to cash crop production, although no adequate training is provided in both cases. Commercialisation skills involve more than just the marketing of output and product choice, but encompasses decisions on input use, which are based on the profit maximisation principle.
V16- V11 Commercialisation skills /Farmer's access to marker as traders		Commercialisation skills in agriculture refer to the ability to move from subsistence-oriented to market-oriented patterns of production and use of inputs (Masuku, 2011). More, a study conducted by (Sicelo Ignatius Dlamini and Wen-Chi Huang, 2019) states that education enhances skills application and information utilization required for marketing in the livestock sector in eSwatini. In the study, the variable is also an indicator for the adoption of innovations and new technology necessary for increasing farm productivity. Based on the significant positive effect of education on market participation, a positive association between the variable and the sales decisions is highlighted by the authors. Although marketing is important, smallholder farmers still find it difficult to participate in markets, especially when faced with pressures from market liberalization. Generally, very few smallholder farmers participate in formal markets. Makhura (2001) investigated the transaction costs barriers in market participation of smallholder farmers in the Northern Province. The author found that marketing by smallholder farmers was constrained by poor infrastructure, distance from the market, lack of assets (for example lack of own vehicles) and inadequate market information. Enhancing the ability of vegetable farmers to reach markets and actively engage in the markets is a key challenge affecting production in Swaziland (Xaba & Masuku, 2012).
V16- V17 Access to education and training / Farming techniques and resource management		The slow development of small-scale growers in Swaziland can be attributed in part to the inability of the Swazi farmers to respond positively to new ideas. For farmers to respond positively to new ideas, they must be properly educated on how best to apply the new ideas to their farming activities, more increased agricultural productivity depends primarily upon the acceptance of cultural and technological changes at the rural farm level ADDIN ZOTERO_ITEM CSL_CITATION {"citationID":"OOweaKbw","properties":{"formattedCitation":"(FAO, 2019)","plainCitation":"(FAO, 2019)","noteIndex":0},"citationItems":[{"id":201,"uris":["http://zotero.org/users/local/lyptmgs7/items/4JJ2TZT2"],"uri":["http://zotero.org/users/local/lyptmgs7/items/4JJ2TZT2"],"itemData":{"id":201,"type":"article","title":"Support to the incorporation of climate Smart agriculture in swaziland schools and Agriculture training centres

		programmes","author":[{"literal":"FAO"}],"issued":{"date-parts":[["2019"]]}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} (FAO, 2019) (Dlamini and Worth, 2016). Training in fact is an essential resource input for all contributors to the process of technological change and agricultural growth.
V17 - V1 Farming techniques and resource management / Small-scale food production		One of the major factors affecting small scale production concerns the need to adopt Climate resilient agricultural practices which lead to a sustainable management of natural resources and input, reducing land degradation and ensuring the availability of resources also in remote areas. In order to improve communities' resilience and management of natural resources the Government of Swaziland adopted an approach that focuses on climate change adaptation through resilient agricultural practices. This has involved the introduction of Climate Smart Agriculture (CSA) techniques such as Conservation agriculture (CA), Agroforestry (AF), the use of drought tolerant crops and the use of quality seed for specific ecological areas. the shift from conventional agriculture to CSA has the potential to intensify and stabilize food production by engaging children and youths in innovation and fostering new enterprises for income generation for smallholder farmers (FAO, 2019). [Although the adoption of such practices is limited by the low qualification of national extension officers which provide inconsistent technical advice to farmers since are not equipped to provide up-to-date information about existing technologies, and they do not have the capacity to involve farmers in adaptive trials of promising new technologies (Worldbank, 2011); more, the Governmental interest on sugar cane production involves small scale producers in the adoption of monoculture production, with relevant environmental impacts.]
V12 - V23 income from agriculture / Access to financial credit	L+	The lack of credit to SMEs (small and medium-sized enterprises), including farmers, can be attributed to several factors, including the perception that businesses are highly risky for lenders (AFI & SMEF, 2018). Income, lack of access to collateral and strict loan conditions that require corporate performance documentation are the main constraints on access to credit. Most SMEs in the country do not borrow from banks, while some borrow from informal mechanisms, friends and families. United Nations Youth Entrepreneurship for Swaziland (2012) determined that 57% of entrepreneurs have used money from friends and family to start or run their businesses. The FinScope Swaziland Consumer Survey (2014) found that only one in five adults in the country earns their source of income in the formal sector, which acts as a guarantee. Community-based credit and savings groups (CBSCG), sometimes called savings and accumulated credit associations (ASCA) and revolving credit and savings associations (ROSCA), albeit informally, also constitute a very critical avenue for access to funding for MSME farmers. Most households face severe budgetary constraints, thereby limiting their ability to finance business start-ups with personal savings. Recently there has been a growing interest from banks to increase their reach in the SME sector, as indicated by their participation in financing small sugar cane growers on SNL, the formation of SME Departments within of some banks and the development of some of their products to satisfy SMEs and farmers.
V24- V23 Land policy / Access to financial credit	L+	Agriculture is one of the sectors that the government of the Kingdom of Eswatini (GoE) has prioritized within small and medium-sized enterprises, in order for the sector to help improve livelihoods and create jobs. According to the Kingdom of Eswatini Household Income & Expenditure (2010), only 4.2% of local households could produce enough food for their own consumption.

		The Making Access Possible (MAP) for MSME Eswatini Diagnostic Study (2018) established that only 22% of SMEs have access to formal credit. In 1990, the Small Business Loan Guarantee Scheme (SSELGS) was established by the government with the aim of encouraging financial institutions to increase lending to small businesses in the Kingdom of Eswatini by reducing the risk of lending to these entities. To qualify for a guarantee, assets must be profitable and fully licensed with Swazi's majority shareholders and be able to provide 25% security on the required loan. A further factor affecting smallholder farmers' access to credit is that the SNL land allocation follows customary law whereby the householder approaches the traditional chiefdom authority under which he undertakes to request a piece of land to build a farm and grow crops. The head of the family is granted the rights to use the land and not the property as it is common land. There is no written evidence of land use rights, for this reason SNL cannot be used as a guarantee for access to credit (Manyatsi & Singwane, 2019).
V23 - V21 Access to financial credit / availability of production input	L+	Access to credit is a crucial factor for the development of the agricultural sector. Agricultural producers rely on credit facilities to raise the capital needed to start and sustain production activities. The role of credit in agricultural production is crucial because inputs such as seeds and fertilizers are purchased at the beginning of the production season, but returns are realized only at the end of the season. The provision of credit was considered an important tool for increasing the incomes of rural populations, mainly by mobilizing resources for more productive uses. The use of fertilizers and other inputs in Swaziland is limited by small farmers' limited access to credit (WorldBank, 2011). Farm credit plays an important role in increasing agricultural productivity in developing countries such as Swaziland. According to ADDIN ZOTERO_ITEM CSL_CITATION {"citationID":"6yK6sCXh","properties":{"formattedCitation":"(S. Dlamini et al., 2019)","plainCitation":"(S. Dlamini et al., 2019)","noteIndex":0},"citationItems":[{"id":220,"uris":["http://zotero.org/users/local/lyptmgs7/items/YKP3X3UA"],"uri":["http://zotero.org/users/local/lyptmgs7/items/YKP3X3UA"],"itemData":{"id":220,"type":"article-journal","abstract":"The agricultural sector in Eswatini is viewed as an engine to foster economic growth, reduce poverty and eradicate inequality. The purpose of the study was to investigate the effects of monetary policy on the agriculture Gross Domestic Product (GDP) in Eswatini using annual data for the period starting from 1980 to 2016. Using the Vector Error Correction model (VEC), the empirical results indicated that in the long run, agriculture GDP, exchange rate, interest rate, inflation, broad money supply, and agriculture credit have a negative effect on agriculture GDP in Eswatini. In the short run the study indicated that the variation in agriculture GDP is largely significant caused by the lagged agricultural GDP, interest rate, exchange rate as well as inflation. Money supply and agriculture credit contribute 0.46% and 0.55%, respectively to the variation in agricultural GDP. The study recommends that programs aimed at availing affordable credit to farmers should be prioritized to cushion the agriculture sector against adverse monetary policy shocks in the short to medium term, specifically interest rates, to ensure continuous production.","DOI":"10.32861/ijefr.55.94.99","source":"ResearchGate","title":"The Effects of Monetary Policy on Agricultural Output in Eswatini","author":[{"family":"Dlamini","given":"Sotja"},{"family":"Dlamini","given":"Daniel"},{"family":"Mashinini","given":"Mary"}],"issued":{"date-parts":[["2019",5,14]]}}}],"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"} (S. Dlamini et al., 2019) (Muhammad L., 2003) the growth of agriculture depends on an increased use of agricultural inputs, technological changes and technical efficiency. These funds could come from farmers' savings or loans. In less developed countries such as Swaziland, where savings are negligible especially among small farmers, agricultural credit becomes an essential input along with modern technology for greater productivity. The credit requirements of the agricultural sector have increased rapidly in recent decades due to the increase

		in the use of fertilizers, the improvement of seeds and mechanization, and the increase in prices.
V20 - V21 Cost of input / access to input, tools and machinery	L-	Most of the inputs and agricultural tools available in Swaziland are provided by private companies related to parent companies in South Africa. Swaziland-based companies and individual farmers are prohibited from directly importing inputs and tools from South Africa, so they must purchase locally from the limited number of authorized suppliers. This limits competition in the market and generally makes inputs and tools expensive. The high cost of inputs and tools is compounded for poorer farmers by the lack of access to short-term production credit needed to finance inputs, especially fertilizers. Finally, as a landlocked country, Swaziland is dependent on freight transport over long distances, which makes it particularly vulnerable to rising fuel prices. Subsistence-oriented farmers on SNL are particularly vulnerable to rising transportation costs, as they cannot pass on increases in energy costs to end users (WorldBank, 2011). Most rural households do not have access to inputs due to the poor financial situation. The poor performance of the agricultural sector in eSwatini is attributable among other things to the increase in the prices of agricultural inputs that small farmers cannot afford, poor market structures, lack of adequate research, existing monopolies in the marketing of agricultural inputs (Government of Swaziland, 2009).
V19 - V20 Availability of production subsidies / Cost of input	L-	The term subsidy covers a broad range of governmental economic interventions and policies. It can be best defined as the financial assistance provided by government to farmers through government-sponsored price-support programs (Food and Agricultural Organization, 2015). The Kingdom of Eswatini introduced an agricultural input subsidy programme in 2014 that was targeted to improve maize productivity among the small-scale maize farmers. According to the National Maize Corporation (2016), in 2014/15 to 2015/16 the area under maize production dropped significantly by 47 percent that led to the drastic decline of production output by 59 percent, which then led to the decline in the country maize self-sufficiency from 62.2 percent to 25.2 percent within the same period. The most common challenges faced by these smallholder farmers include increasing cost of buying farm inputs such as seeds, fertilizer, chemicals, hiring tractor for farm operations and the climate change effect, which has forced some farmers to halt maize production just to focus on food aid. The benefit generated by policy may take different forms such as an increase in output-price, reduction in input-price, tax rebate, interest rate concession and/or direct budgetary transfer. In order for developing countries to achieve productivity that are financially viable by the small-scale farmers there is need to have adequate inputs and proper technologies. The package of the Kingdom of Eswatini subsidy programme requires that the maize farmers should register and the registered farmers contributes by paying 50% of the cost for one 25 kg bag of maize seeds, four 50 kg bags of LAN fertilizer and six 50 kg bags of NPK fertilizer (S. Dlamini et al., 2019).
V21 – V22 Access to input, farm tools and machinery / Yield Crop	L+	The Yield is influenced by the ability of farmers to cope with agricultural needs in rural areas. As we already know, small subsistence farmers are found in remote rural areas where the availability of agricultural inputs is scarce. Irrigation infrastructure is developing in the country with a focus on growing small-scale sugar cane production for international markets, while major rural areas are not served with this service and water is often not available in nearby areas. Farmers' access to financial services would allow for investment in land and access to inputs in order to increase crop yields. In the study conducted by (S. Dlamini et al., 2020) the difference between the average productivity of small farmers who participated in the agricultural input subsidies program and those who did not participate increased to 0.13 tons / ha. These findings imply that participation in the adoption of the agricultural input subsidy has a positive effect on the corn productivity of smallholder farmers in the Hhohho region of

		Eswatini. These findings are in line with the findings of (Oladejo, C. , 2018) who also found that agricultural subsidies had an impact on productivity. However, it should be considered that subsidies include a training aspect regarding the use of agricultural inputs, in fact the knowledge gaps on the management of agricultural inputs represent a limiting factor in their use (Masuku, M.B., 2011).
V3 - V22 Water availability for farmers /Crop yield	L+	Agricultural production takes place in an environment characterized by risk and uncertainty. This is especially true in arid and semi-arid areas where the water supply to crops from rainfall is variable and erratic. Even in irrigated areas, water scarcity is not uncommon and yields are often affected (FAO, 2012). Plant growth and development are known to be affected by abiotic agents such as salinity, high temperatures, radiation, flooding and water deficit. The exacerbated action of these environmental conditions can lead to large productivity losses due to crop stress. In a water deficit situation, plant responses can be species / genotype specific. If the stress intensity is moderate or severe, plants tend not to recover. Climate change strongly affects the availability of water and therefore the yield of crops in both TDL and SNL. In 2015/2016 the effects of El Nino were evident throughout the national territory as agricultural activities were hindered. The cultivated area decreased significantly as a 65% decrease was observed compared to the previous season (2014/15). This had a significant impact on overall production, especially corn as a staple food for the country. In general, the poor yield was attributed to: fallow fields, crop failure, poor germination rate and extremely high temperatures mainly due to drought (SwGov, 2016).
V22 - V1 Crop Yield / Small-scale Food production	L+	An increase in crop yield would drive farmers to an increase small scale agricultural subsistence production.
V22 -V15 Crop yield / income from agriculture	L+	Farmers who sell their produce have a surplus (Banele Nhlengethwa, S. S., & Nhlengethwa et al., 2020). Therefore, the failure to sell the product is due to the lack of surplus with production only for domestic consumption. In addition, Swaziland's farmers, and especially smallholder farmers, face enormous challenges in finding markets for their produce. Local markets are often flooded with cheap imported products, which sometimes enter the country without any quality control. The commercialization of agriculture refers to a shift from production for consumption to market-oriented production that guarantees the sale of products. This not only increases the market share of agricultural production, but also leads to greater productivity, quality and specialization of work. Market participation can lead to lower food prices due to increased market competition, which reduces food processing and market costs. This improves the general welfare of Swazi farmers by increasing their purchasing power for food and redistributing a limited family income (Lucinda N. Dlamini, 2019).
V15- V21 income from agriculture / access to input, tools and machinery	L+	A 1994 Leliveld definition defines that only 9% of farmers in SNL are classified as rich farms that have excess equivalents to poor farms. In general, affluent farms have the means available (they are much better equipped and make use of modern inputs) to increase agricultural production, compared to other categories that depend on renting tractors and / or oxen and plows. Agricultural inputs are mostly provided by a small number of private companies, most of which are related to parent companies in South Africa. Although inputs are generally available on the market, the competitiveness of the sector is very limited, partly because producers cannot import inputs directly from South Africa, but must

		instead rely on companies established in Swaziland (WorldBank, 2011), whose costs are often inaccessible for rural households.

Appendix 2.

ODD Protocol (Grimm, 2017) **for:**

An agent-based modelling to explore factors influencing individual decision-making processes in a Social Learning environment.

1. Research Question and Purpose

The Agent Based Model will be used to answer the specific Research Question: what is the effect of social behaviour on smallholder subsistence farmers resilience to food insecurity and environmental degradation? The model goal is to include social factors such as power/status relations and cultural behaviours which drive individual's decision in adopting innovative agricultural practices in order to explore the factors affecting the diffusion of knowledge and the adoption of new behaviours in rural communities in eSwatini (southern Africa). In this context resilience refers to the adoption of more sustainable practices (Conservation Agriculture practices) as representative of short-term and long-term adaptation to harsh environmental conditions, in a context of growing uncertainty linked to climate changes and common food insecurity strongly related to high poverty rates in the area. Short term adaptation refers to the capacity of increasing food production to face food insecurity issues; while long-term resilience refers to the improved management of natural resources such as water and soil which allows an increase in resources availability over time while improving environmental health. Social Learning theories (Bandura, A., 1977) stand as the theoretical base of how the individual decisional process takes place. This assumes an iterative feedback between the learners and their environment which means the learner changing the environment, and these changes affecting the learner. In Social Learning models, individuals apply multiple observations to reach a general theory/conclusion which is then based on personal experiences and the behaviour and experiences of others they know personally. The learning process is driven by individuals' intention/propensity to adopt a certain behaviour, which is highly dependent on the surrounding socio-cultural context and on the relationships between the different members of the community. The agent-based model was implemented in the Netlogo 6.2.0 platform (Tisue, S., & Wilensky, U., 2004) and follows the more recent literature inspired by (Nowak, 2017) that incorporates both individual and social learning components in each agent; this more realistically captures how human learning takes place. Environmental assumptions concerning each agricultural practice in the study are based on literature.

2. Entities and State variables

The model comprises N connected social agents and ecological agents. Ecological entries are modelled as Resources units available in each patch, this value is independent from other patches and are recovered at each run. Patches own a memory related to yield produced in the previous years (memory length is set by the observer before the simulation starts), input and resources consumed which then is available as information from farmers. Farmers are characterized by their location in the community and hence the distance from other households and from training structures, the availability of farmland in which they adopt a certain practice, the input available for production, their memory of past yield deliveries and its variation, input and natural resources consumed. Also, individual factors have been included in the model, such as gender, education level and household size with an effect on final behaviour adoption. Farmers learn information individually and socially concerning productivity, input and natural resources consumption related to a certain agricultural behaviour, which are then used for the evaluation of outcomes based on Input Security and Yield stability thresholds. Individual factors act as external or internal bounds or reinforcements to the adoption of the willed practice so as the effect of traditional power which affects the decisional process of individuals defining heterogeneity among agents and influencing their perception of Risk and propensity to involve in adaptation strategies. Input security is intended as the requirement of input needed to adopt a certain behaviour; while Yield Security is related to the productivity variance. A minimum input requirement is also set in order to involve in any agricultural practice. Outcomes are evaluated by agents using voting schemes, which can be individual: defines whether the self-produced outcome fulfils expected requirements of security and stability or not and influences agent's preference to involve in one or another practice; or a social voting scheme which results from observed behaviours in the social Network, affecting agent's intention. In the final step voting schemes are used to define the adoption of a behaviour depending on individual factors, the so-called Adaptation propensity.

3. Process overview and scheduling

At the start of each agricultural season (1 tick), a sequence of activities takes place in the order as shown in Fig. 2A. At the beginning of the run consumed resources are subtracted from available natural resources on each patch depending on the practice adopted by the agent in that run. The agent's adoption of a certain agricultural behaviour is the result of the Learning and decision-making process (Fig. 2B) and is dependent on the following factors: a. productivity factors such as resource and input availability and access, which in the model are linked to two main features (thresholds): minimum input requirement to involve in any practice and the Security in Input availability; b. individual characteristics which affect agents Adaptation propensity to innovation and Risk evaluation and c. the learning processes which defines the intention of an agent in adopting traditional or sustainable practices. Individual properties refer to education level, the effect of power on accessing resources and services which in the model is representative of gender discrimination, the spatial location of agents in relation to centres and the size of the household which positively affects the adoption of CA practices. Agents' learning process occurs as a consequence of *social behaviour*. Agents dynamically interact in the network and base their *intention* on two possible forms of learning: an individually based and a socially based learning. Follows the adoption of the decision. Decision making in the model is linked to the evaluation performed by the agents of their propensity to adopt innovation (Adaptation propensity) when the observed behaviour in the network leads to CA. When final evaluation on adaptation which considers both individual factors and the learning process is positive agents will perform CA, else traditional. Agents which adaptation propensity equals to zero instead will evaluate their risk perception and adopt no cropping or traditional based on individual factors evaluation. For model equations refer to the Sub models section below. When the decision is adopted by the farmers the social behaviour ends and natural resources and input are recovered in patches before the new run starts.

4. *Design concepts*

In the model farmers are connected through social circles (Hamill, L. and Gilbert, N. , 2015). Each time an individual has an experience (defined as a coupled behaviour/outcome pair), the agent will relay the experience to others in the social network in the form of anecdotal information. We assume here that geographical distance determines social distance. The agent's decision model assumes that their behaviour is affected by individual and environmental learning factors, so as reported in the Social Leaning Theory (Albert Bandura, 1977). Agent's satisfaction in the simulation is reached when a certain outcome is achieved in relation to the overall goal: increase agricultural productivity, Input Security and Yield Stability. The achievement of these targets is affected by agent's internal evaluations and beliefs which are strongly influenced by observed outcomes in the social network, by status-power interaction and by individual factors.

5. *The decision-making process*

Agents' adoption of a certain behavioural practice is driven by individual perceptions which emerge from interactions in the network. Each individual farmer decides which agricultural behaviour to adopt. The amount of input and natural resources determines the practice in which agents can involve. The agents pursue the objective of maximizing their yield while ensuring Yield Stability. Agents try to find the best strategy by adapting the behaviour based on an evaluation of their past performance, other outcomes and behaviours, the effect of status-power on agent's, their propensity to adopt new practices and the risk perception and evaluation. They do so by a continuous comparison of their performance and consumptions with the thresholds for input security and yield stability based on yield variance. Social norms and cultural values play a key role in influencing individuals' behavioural decision, in this simplified model few individual parameters have been implemented which have an effect on the learning process. A focus is given to the role of this factor in the overall learning process occurring as a result of interaction between agents and their social network.

a) ***Learning***. This occurs both individually and in an iterative feedback process between the learners and their environment. individual and social leaning in the model affect the propensity of an agent to involve in a certain agricultural behaviour between no cropping, traditional agriculture and Conservation Agriculture. Social learning in the model occurs when others in the network of the agent have higher status, which means higher crop production and higher education. Social learning results in a voting scheme which defines the intention to involve in traditional or sustainable practices based on the more adopted behaviour among observed agents in the network (Eq. 4):

$$(4)\ Social\ Vote\ practice = \frac{(number\ of\ agent\ with\ sustainable - number\ of\ agent\ with\ traditional)}{total\ number\ of\ agent\ produce\ more\ than\ itself\ with\ higher\ education}$$

In individual learning, if no agents with higher status are present in the network, the farmer will perform individual Vote practice based on self-yield variance. The preference in adopting CA or traditional practice refers to the variance acceptance threshold which value is set by the observer at the start of the simulation. Values of yield variance above the threshold define the preference in adopting more sustainable practices, defining 1 in the Individual Vote practice (Eq. 5):

$$(5)\ Variance\ crop\ produce = Var[crop\ produce_t, crop\ produce_{t-1}, \dots, crop\ produce_{t-n}]$$

$$t - n = memory\ length$$

In both learning processes agents vote 1 when preference is CA, -1 when traditional. Voting schemes are used in Final decision making by agents.

In the model an additional factor influences the adoption of CA practices, which is linked to the interaction of agents with training centres. Training centres affect agent's education level with effects on its adaptation propensity and risk evaluation which represent the last steps of the decision-making process (Eq. 6 and 8)

(6) $$Adaptation\ propensity = gender + access\ to\ community\ resources + access\ to\ training\ + Household\ size$$

(8) $$Risk\ evaluation = gender\ *\ level\ of\ education\ *\ power\ effect\ *\ individual/social\ Vote$$

b) ***Sensing***. Farmers know the amount of input and resources available for their fields, they own memory, the natural costs of production and the crop yields. Agents' spatial scale is local. Individuals share and receive information of behaviour and outcomes in the network through the learning process (see previous paragraph). The information collected by farmers concerns the most common practice adopted by other agents with higher status in the network. In individual learning agents evaluate the variance collected in the memory years related to crop production, defining if the outcome fulfils the expectations through the comparison to a Yield Variance threshold which is set at the start of the simulation by the observer. The final decision in adopting a behaviour is influenced on one side by the learning process, on the other side by individual factors. The intention to adopt CA or traditional is the result of the observed outcomes in the network or based on self-evaluation and is included in the model through the Voting System for which a Social Vote practice and an Individual Vote practice are performed (Eq. 4 and 5). On the other side the final decision (Eq. 7) of an agent to involve in the selected practice is dependent on various individual factors such as the experience in farming, the power effect and the size of the household, all affect agent's final adoption of one or another practice. Adaptation propensity (Eq. 6) and risk evaluation (Eq. 8) are the two processes involving individual conditions affecting the behaviour.

(6) $$Adaptation\ propensity = gender\ (*\ 1) + access\ to\ community\ resources (*\ 1) + access\ to\ training\ (*\ 1) + \ Household\ size (*\ 1)$$

(7) $$Final\_adaptation\ =\ (individual/social\ Vote\ *\ Adaptation\ factor)$$

(8) $$Risk\ evaluation = gender\ (*\ 1) *\ access\ to\ community\ resources (*\ 1) + access\ to\ training\ (*\ 1) + individual\ Vote$$

No cropping is adopted when final adaptation is 0, access to training is 0 and individual vote practice is 1, defining the preference to adopt sustainable as a consequence of high yield variance, no information available and no one in the network performing better. Else, agents will adopt traditional practices.

c) ***Adaptation***. Adaptation in the model is strictly related to farmers individual characteristics which influence the final decision of the agent (Eq. 7). Agents base their propensity to adopt innovation on factors such as gender, access to community resources and training (effect of power) and the size of the household in a process of continuously assessing decisional alignment with accepted behavioural outcomes based on the combination of the information acquired during the learning process and the evaluation of the outcomes concerning resources and input availability.

(6) $$Adaptation\ propensity = gender +\ access\ to\ community\ resources + access\ to\ training\ +\ Household\ size$$

(7) $$Final\_adaptation\ =\ (individual/social\ Vote\ *\ Adaptation\ factor)$$

Pseudo-code in Netlogo reporting Adaptation propensity evaluation

```
    set Adaptation_propensity (gender + community_resources_access + access_to_training +
family_size_adaptation)
    ifelse adaptation_propensity > 2 [
        set Adaptation_factor 1] [
        set Adaptation_factor 0]]
```

The threshold is set at 2 since is representative for women which practice mainly traditional agriculture due to limited access to training and community resources. Women gender factor (value = 2) is a sufficient condition to involve in traditional practices and not change to no cropping unless not enough resources are available in the patch. The evaluation is performed both by men and women and defines the acceptance of the innovation. Adaptation factor is then used in final decision to select the final behaviour:

Pseudo-code in Netlogo reporting Final adaptation decision

```
    ifelse total_vote_practice = 0 or total_vote_practice1 = 0 [    ;; means no one with higher status
is in the network, agents base their decision on individual learning;;
    set Final_adaptation (individual_vote_practice * adaptation_factor)

    if total_vote_practice1 > 0 [              ;; someone with higher status is present.  Social learning is
performed;;
    set Final_adaptation (social_vote_practice * adaptation_factor)
```

Culture and traditional law strongly impact on individuals decisional process playing a key role in agents decision making and propensity to adapt to innovation affecting the overall system's resilience in relation to food insecurity. In the model adaptation can be seen in the long-term as natural resources availability over time, which is shown to be higher for conservative practices rather than traditional. Although initial differences in yield productivity between the two practices are low, long term evaluations highlight a higher availability of natural resources with effects on crop productivity over time. In the model this results in a fraction of farmers willing to adopt CA after a certain time in which the increase in production which initially is comparable to traditional practices, is boosted due to the higher availability of natural resources (Eq. 3):

(3) $Crop\ produce_t = input\ used_t * \frac{natural\ resource\ used_{t-1}}{100}$

*Nat_resources_used (t-1) /100 represents the natural resources factor, which is a resources degradation factor (in %) related to each agricultural practice. The factor is then compared to the natural resources threshold and defines the preference to CA or traditional in the next farming year:

Pseudo-code in Netlogo reporting natural resources evaluation in individual vote

```
ifelse ( natural_resource_factor < natural_resource_threshold ) [     ; if the threshold is exceeded
set individual_vote_practice 1                                         ;; preference adopting sustainable
    ] [
      set individual_vote_practice -1]                                 ;; else, preference traditional
```

d) ***Interaction***. Interactions between individuals are selective on those showing better performance and higher status, affecting perception of good or bad expected outcomes. Individual factors affect this process and agent's intention. Social learning in communities is defined as the main (informal) mechanism for knowledge diffusion and also in this case is strictly related to cultural habits and traditional laws acting as a bias in the spread of knowledge in the system and the adoption of sustainable agricultural practices. More, access to formal education (centers) is limited by gender discrimination and physical distance.

e) ***Heterogeneity***. The model considers the following individual factors as the ones driving heterogeneity: agents differ on their randomly assigned family size value which has an effect on the adaptation process; gender is assigned to agents; education level is based on access to formal training. No one of the listed factors are under the model user control since are set randomly at the start of the simulation. Values are reported in Table 5 and are set based on gender differences and spatial location of agents in the model:

Table 5 individual factors driving heterogeneity in the model

	Men	Women
Gender	1	2
Household size	1 to 9	1 to 9
Access to community resources	1	0
Access to community training	0 or 1	0

The factors in Table 5 are used in the process of Adaptation propensity and Risk evaluation (Eq. 6 and 8).

f) ***Stochasticity.*** The model has the following stochastic sources: the position of the people in the field is random so as the links to connect to other individuals in the network. Natural resources and input availability are set randomly in the model patches based on a defined range of values, agent's initial distribution on patches defines their position for the entire simulation affecting the adoption of behaviours based on resources and input availability, consumption and recovery. The control of the model user on these factors is reported in Table 6:

Table 6 Stochasticity in the model

Variables	**Setup**	**User control and randomness**
People	The number of people in the simulation is set before it starts.	The number is selected from the user of the model, although the distribution is random, defining agents position for the entire simulation.
Gender	Gender is defined during model initialization	The user has no control on the definition of agent's gender.
Household size	Household size is defined during model initialization	The user has no control on the randomly assigned values.
Number of links	Defined during setup by the user	The number of links for each agent is under the control of the user although its creation is randomly defined by the software.
Education centres	Number of education centers is under the control of the user at the initial step	The distribution of centers is randomly assigned by the model
Natural resources	In a range 80 ± 10	The amount of resources available is defined in the setup with values randomly assigned to patches. The User has no control on the availability to farmers.
Input availability	Input ranges change according to the initial practice in which agents are involved.	The value is randomly assigned according to the expected values for a certain practice. The user does not have a control over it.

6. Initialization

Individual agents are defined as equivalent, which means that they have the same attributes: only the values of these attributes vary, defining each agent and its characteristics. The model setup button is under the user's control. The model runs as follows:

1. Patches equal to the number of people selected by the user (presence of a slider in the interface) are randomly generated throughout the landscape. They will be assigned with random initial natural resources together with an empty list to store input used, natural resource used, and crop produce by turtles.
2. Agents are assigned with initial Minimum Input Threshold, Input Security Threshold, Yield Stability Threshold, Yield Variance Threshold, Natural Resource Threshold, Self Confidence Level, and Stability of Yield, initial education level, risk perception and household number of individuals.
3. Each agent is randomly assigned one out of three initial farming practice behaviours (no cropping, traditional and sustainable). Initial number of individuals for each practice is defined by the user in the interface (sliders). Then input available to agents is assigned based on these behaviours since it is assumed that agents have some difference in their socio-economic status which define their initial behaviour. Initial input is transmitted to patches and at the same time natural resources available on patches are accessed by agents and stored in agents for later use. Lastly links are created randomly to connect agents and equals to number of spatial link size selected by the user.

6.1 Input and parameters setup

Initial parameters are set arbitrary since the aim of the model is to understand emerging patterns from social learning approaches.

- Parameters related to farming practice: in Table 7 the availability, use and recovery of natural resources and input is qualitatively defined for each behaviour.

Table 7 Qualitative description of: availability, use and recovery of natural resources and input defined by farming practice

	No cropping	Traditional agriculture	Conservation Agriculture
Input availability	/	low	medium
Input used	/	low	low
Input recovery	/	low	low
Natural resources availability	/	medium-low	medium-low

Natural resources used	/	medium-low	medium-low
Nat resources recovery	/	low	high

- Input used are lowest with no cropping higher with traditional and slightly higher with Conservation Agriculture, assuming CA practices allow for higher in- farm availability of input.
- Input available are lowest with no cropping and highest with CA, since it is more likely that someone practicing no cropping is not interested in allocating their economic resource to be used as input and traditional practices allow for low in-farm availability.
- Input recover are lowest with no cropping and similar for traditional and CA.
- Natural resources used are lowest with no cropping and similar when referring to traditional or CA , in fact the two practices differ on the recovery factor of resources rather than on its consumption.
- Natural resources recovery are lowest with traditional and highest for sustainable since CA is known for high resources management and soil health.

Initial parameters

- Natural resource are set similar to all practices except no cropping.
- CA and traditional practices consume similar amounts of resources.
- Ca practices recovery is slightly higher than traditional

7. Submodels

Table 8 Table reporting parameters and variables in the model

Variables and parameters	**Symbol**	**Meaning**	**Equations**	**Nominal value**	**Dimensions**
People	P	Number of people defines the population density in the field. The variable is set by the model user through a slider in the interface.		300	unit
Spatial link size	L	Defines the number of independent connections of the agent in the network. The variable is set by the model user through a slider in the interface.		3	unit
Mean yield variance threshold	Vt	Defines the accepted variance in crop produced over the years. Cro produced is stored in memory. The variable is set by the model user through a slider in the interface.		2	unit
Memory length	M	Crop produced over the years is stored in memory. The values are used in individual learning to evaluate production variance. The variable is set by the model user through a slider in the interface.		4	unit
Number of education centers	Ct	Education centers represent the external input to the adoption of sustainable practices. The variable is set by the model user through a slider in the interface.		2	unit

Gender	S	Gender has been set to represent the discrimination of traditional law on agents. Gender is used in decision making and is representative of farming experience. A higher value in fact is set for women.	Eq. 6 Eq. 8	1= male 2= female	N/A
Education	Ed	Education is the result of the interaction of agents with the training centers. An increase in education level results in higher propensity to adopt "sustainable".	Eq. 8	0.5 for initial sustainable farmers; 0 for all other agents	N/A
Access to community resources	Re	Community resources (land) are accessible only for male farmers as a result of the power effect. Is used in decision-making.	Eq. 6 Eq. 8	1 = male 0 = female	N/A
Access to training	Tr	Refers to the centers located randomly in the field. Access to training Is used in decision-making and is representative of the power effect on women.	Eq. 6 Eq. 8	1 or 0= Based on gender and location	N/A
Household size	Fy	Number of individuals in the household. The variable affects the decision-making.	Eq. 6 Eq. 8	1 to 9 Randomly assigned	unit
Number of no cropping	x	Number of agents to total which adopt initial practice "no cropping". The variable is set by the model user through a slider in the interface.		Initial value= 0.0 %	unit
Number of traditional	y	Number of agents to total which adopt initial practice "traditional". The variable is set by the model user through a slider in the interface.	Eq. 4	Initial value= 0.8 %	unit
Number of sustainable	z	Number of agents to total which adopt initial practice "sustainable". The variable is set by the model user through a slider in the interface.	Eq. 4	Initial value= 0.2 %	unit
Input available	Ia	Input in the model is representative of water and fertilizers availability. The variable is updated based on consumption and recovery rates. Equation one refers to the	Eq. 1 Eq. 10	Initial values No crop= 5 ± 2 Trad= 25 ± 5 Sust= 45 ± 10	mass
Input used	Iu	Inputs are consumed by agents with rates based on the agricultural practice adopted. Input used affect input available at the start of each production season.	Eq. 1 Eq. 3 Eq. 10	No crop= 0 Trad= 5 + 2 Sust= 5 + 4	mass
Input recovery	Ir	Inputs are recovered at the end of each run with similar rates for the traditional and sustainable practice. Input are recovered at the end of each run	Eq. 10	No crop= 0 Trad= 2 - 0,5 Sust= 2 - 0,5	mass
Natural resources available	Na	Natural resources are representative of ecosystem services in the model i.e., soil health and fertility. The variable is updated based on consumption and recovery rates.	Eq. 2 Eq. 11	Initial value= 80 ± 10 Max value= 100	N/A
Natural resources used	Nu	Natural resources are consumed by agents with rates based on the agricultural practice adopted.	Eq. 2 Eq. 3 Eq. 11	No crop: 0 Trad: 2 + 2 Sust: 2 + 2	N/A

Natural resources recovery	Nr	Natural resources are recovered at the end of each run with rates based on the adopted practice.	Eq. 11	No crop: 0 Trad: 1 – 0,5 Sust: 2	N/A
Min input threshold	mtr	Minimum input threshold is used in decision-making to define the adoption of no cropping or traditional practices.		15 ± 2	mass
Input security threshold	Ist	Input security threshold is used in decision- making. If reached allows to change from traditional to sustainable.		30 ± 5	mass
Intention of farmers	Int	The Learning process is used to keep track of the propensity of agents to involve in one or the other practice before final decision is adopted. In the model, the monitor “intention of farmers” allows to observe farmers preference as a result of the learning process	Eq. 9	15 ± 1	
Natural resources threshold	Nt	Natural resource threshold is used in individual learning making decision between sustainable and traditional practices.		0.50	N/A
Crop produced	Cp	Input used and natural resource used determine crop production.	Eq. 3	/	mass
Risk evaluation	Re	The factor is representative of agent’s perception of its capacity to face risk and uncertainty in agricultural production and results in the adoption of no cropping or traditional practices.	Eq. 8	1 when adopting no cropping -1 when adopting traditional	N/A
Social Vote practice	SV	In social learning the intention of an agent to involve in traditional practices or CA is based on the evaluation of others with higher outcomes and status in the social network. The most common practice adopted in the network influences agent’s propensity to adopt.	Eq. 4 Eq. 9		unit
Variance crop produced	Var	If no agents with higher status are present in the network, the farmer will perform individual Vote practice based on self-yield variance. The variable is related to Memory length.	Eq. 5		mass
Individual Vote Practice	IV	The variance of crop produced is referred to a threshold to define agent’s preference in adoption. When the threshold is overlapped agents, intention would be to adopt sustainable practices. Else, agents will keep their condition of traditional farming.	Eq. 9	1 when preference is sustainable; -1 when preference traditional	N/A
Adaptation propensity	Ap	Adaptation propensity is performed by agents next to the learning process in which a preferred behavior is defined.	Eq. 6	1 when adaptation conditions are respected; 0 when not.	N/A

- ***Production***

Production will determine input and natural resources used according to each farming practice. Input and natural resource are two separate stocks and their availability will be reduced by input used and natural resource used by agents (Eq. 1 and 2).

$$(1)\ input\ available_{i,t} = input\ available_{t-1} - input\ used_t$$

$$(2)\ natural\ resource\ available_{i,t} = natural\ resource\ available_{t-1} - natural\ resource\ used_t$$

Index *i* lists the indicator of each agent / patch.

Input used and natural resource used determine crop production. However, in real life crop production usually depends on how natural resource are depleted (what remains and not what is consumed) hence in the model it is assume that crop produce is determined by (Eq. 3)

$$(3)\ crop\ produce_{i,t} = input\ used_t * \frac{natural\ resource\ used_{t-1}}{100}$$

This is not realistic but as mentioned before the current purpose of the model is focused on Social Learning. The formular is intended to keep the relation simple. Natural resources used is normalized by dividing to its max value. The factor is representative of resources degradation as a result of the performed practice.

Agent then transmit natural resource available and input available to patches and input used, natural resource used, and crop produced onto patch memory list.

- ***The effect of power***.

In the model gender discrimination is represented by the exclusion from accessing community resources and services such as land and training with an effect on agent's Adaptation propensity to a new behaviour and Risk perception related to uncertainty (see Eq. 6 and 8 below);

- ***The effect of status***.

Agents learn socially in the social network from those with higher status, which means agents with higher production and higher education. This results in voting schemes that affect farmers propensity during the learning process;

- ***Agents' spatial location***.

The spatial location of agents refers to the distance from training centres, in the model a male agent located in nearby areas to a centre can access the training and collect education concerning best practices, this positively influences the propensity to involve in Conservation Agriculture.

- ***Compare and Learning***

Compare and Learning consist of Social Learning, Individual Learning and Decision Making.

In the Learning Processes (Fig 2B) agents perform voting schemes defining the propensity to involve in a certain practice. In social learning the intention of an agent to involve in traditional practices or CA is based on the evaluation of others with higher outcomes and status in the social network. Agents with higher status in the model are those farmers which have higher production and higher level of education. A social voting scheme is performed in this case defining the preference based on the more adopted behaviour among observed agents in the network (Eq. 4):

$$(4)\ Social\ Vote\ practice = \frac{(number\ of\ agent\ with\ sustainable - number\ of\ agent\ with\ traditional)}{total\ number\ of\ agent\ produce\ more\ than\ itself\ with\ higher\ education}$$

The formula is selected because the maximum method has a chance to have more than one maximum. The voting is divided by total number to make sure that maximum gain and minimum gain are plus and minus one in the same fashion as individual learning.

If no agents with higher status are present in the network, the farmer will perform individual Vote practice based on self-yield variance (Eq. 5). The preference in adopting CA or traditional practice refers to the acceptance threshold in relation to the variance. Values of yield variance above the threshold define the preference in adopting more sustainable practices, defining +1 in the Individual Vote practice.

$$(5)\ Variance\ crop\ produce = Var[crop\ produce_t, crop\ produce_{t-1}, \dots, crop\ produce_{t-n}]$$
$$n = memory\ length$$

In both learning processes agents vote 1 when preference is CA, -1 when traditional. Voting schemes are used in Final decision making (see below).

- ***Decision-making***

In decision making (Fig. 2B), first agents compare input available and input they are going to recover, with the minimum input threshold. If minimum input threshold is higher than available, agent will adopt no cropping. Then agent will compare crop produce. if crop produce is zero due to depletion of natural resource, agents will adopt no cropping. Next agent will compare input available and input they are going to recover with input security threshold. If input security threshold is higher, agents will adopt traditional. Follows the evaluation of the effect of traditional power in access to resources and training. If an agent has access to resources and training is available, Education-level is set + 0.1, else 0.

In the case of limited access to resources and training agents will evaluate it in both adaptation propensity and final Risk evaluation. Farmers involve in the learning process made of individual or social observation which affects the individual process of evaluation and therefore agents' final behavior.

If no agents produce more than itself or with higher education the farmer will perform Individual Learning, else the agent will do Social Learning. After adopting Social or Individual learning the voting schemes are updated resulting in the preferred practice of the agent.

The Learning process is used to keep track of the propensity of agents to involve in one or the other practice before final decision is adopted. In the model, a monitor allows to observe the preference (Eq. 9).

Equazione 9 $$Intention\ of\ farmer_t = Intention\ of\ farmer_{t-1} + (social/individual)\ vote\ practice\ score$$

agent's preference is set +1 when the learning process results in preference to sustainable practices, -1 when the preference is to traditional as a result of agents learning.

In the model the final decision of the agents considers the Voting schemes, as output of the learning process, the Adaptation propensity and the Risk evaluation. Adaptation propensity (Eq. 6) is influenced by agents' individual factors such as education level, gender (representing farming experience in the model), access to training, and the household size.

$$(6)\ Adaptation\ propensity = gender\ (*\ 1) + access\ to\ community\ resources(*\ 1) + access\ to\ training\ (*\ 1) + Household\ size(*\ 1)$$

Weighting factors are set for each of the parameters affecting the adaptation. The parameters are all weighted with the same value since the parameters are already assigned with a weight (Table 9) representing the effect on the overall equation : the adaptation is based on the comparison with the adaptation threshold of value 2, in fact women adaptation propensity is strongly affected by gender discrimination in accessing natural resources and training for which a 0 value will be set, the adaptation propensity in the case of women is therefore strongly related to the size of the household.

Table 9 weighted values for Adaptation propensity evaluation

		Parameter
Gender	men	1
	women	2
Access to community resources	Men	0
	women	1
Access to training	Men	1 or 0 based on location
	women	0
Household size	Men	Households are provided with a random value of household size in a range 1 to 9. When the size >= 6 agents assign a +1 in the equation When size < 6 agents assign 0 to the parameter.
	women	

Adaptation propensity outcome influences the *Adaptation Factor* by setting 1 if adaptation is positive, 0 if the threshold is not reached. Final adaptation is performed as the final decision of agents involving in CA practices. The outcome can be producing sustainable or move to the Risk evaluation. Final adoption of CA is influenced by the level of education of the agents, individual factors affecting adaptation and the learning process voting scheme (Eq. 7):

(7) $Final\_adaptation = (individual/social\,Vote * Adaptation\,factor)$

Where *Adaptation factor* is the output of adaptation propensity and is set to 0 or 1 depending on the outcome of Adaptation propensity.

Risk evaluation is set as final decision procedure of the decision-making timestep. This factor is representative of agents' perception of its capacity to face risk and uncertainty in agricultural production and results in the adoption of no cropping or traditional practices. Risk evaluation is based on gender, representative of farming experience, the level of education, the effect of power and the learning process (Eq. 8):

(8) $Risk\ evaluation =$

$$gender\ (*\ 1) *\ access\ to\ community\ resources(*\ 1) + access\ to\ training\ (*\ 1) + individual\ Vote$$

Risk evaluation is based again on individual factors, all factors are weighted the same since specific conditions are set for the adoption of a behaviour. Risk evaluation results in the adoption of no cropping or traditional practices. No cropping is adopted when final adaptation is 0 and access to training is 0 and individual vote practice is 1, defining the preference to adopt sustainable as a consequence of high yield variance, no information available and no one in the network performing better. Else, agents will adopt traditional practices.

- ***Resource Recovery***

Resource recovery will add up input recover and natural resource recover back into the available resource. The process is separate from production because is better represents realistic system's behaviours. This can also be used in future model developments to add elements of prediction vs. actual yield, where the prediction can be computed in production and comparison and learning but add up at resource recovery in a later stage. Also, agents transmit available input and natural resource availability to patches updating the values stored.

At the end of each run. Natural resources and input are recovered, updating their availability to farmers for the next run.

Equazione 10 $\quad input\ available_t = input\ available_{t-1} - input\ used_t + input\ recovery_t$

Equazione 11 $\quad natural\ resource\ available_t = natural\ resource\ available_{t-1} - natural\ resource\ used_t + natural\ resource\ recovery_t$

8. Model implementation

Netlogo 6.2.0

Appendix 3.

Residuals plots

Table 10 Residuals plots for OFAT Sensitivity Analysis. 25 repetitions for each parameter are reported.