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Research article

Assessing a potential conflict associated with the production of *Moringa oleifera* in the Limpopo Province of South Africa: A systems thinking approach

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ABSTRACT

The increased movement of humans throughout the world allowed the transportation of several species, such as *Moringa oleifera* Lam. (moringa), into biomes far away from their native habitation. Native to India, moringa is a versatile, drought-tolerant, and fast-growing tree that is easily adaptable to wide-ranging tropical and sub-tropical conditions around the world. It is used in cosmetics, as food and medicine for humans, livestock feed, crop biostimulant, and green manure. Even though moringa is an alien species to South Africa, its production is increasing, and its numerous uses are recognised by communities. Moringa forms part of a highly complex (social, ecological, and economic) system. This is because it is on the Species Under Surveillance for Possible Eradication or Containment Targets (SUSPECT) list under the National Environmental Management Biodiversity Act (NEM:BA) of South Africa. Listing species that are regarded as beneficial to communities on national regulations can cause conflicts and uncertainties among various stakeholders (i.e., environmental policymakers, farmers, rural communities, and government bodies). In this paper, a systems thinking approach was applied to address complex and conflicting issues linked to the production and overall status (economic, ecological, legal, and social) of moringa in South Africa. The Causal Loop Diagram (CLD) was developed to present a broad insight into the complexity of moringa in South Africa and assist in underscoring the feedback mechanisms within the system. Moreover, the CLD indicated that the position of moringa within the country comprised a variety of interdependent variables of government policies, environment, and society, which are interconnected into a multifaceted system. The potential conflict dimensions and types associated with allocating moringa an impact category within the South African context were identified, and this may serve as a useful tool for facilitating engagements and decision-making processes among stakeholders in resolving the status of moringa in South Africa.

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1. Introduction

Biological invasions have been recognised as one of the major environmental problems across the world [1,2]. The increased movement of humans and goods facilitated the transportation of numerous plant species to ecosystems far from their natural habitats [3]. As such, multiple alien plant species have been introduced outside of their native ecosystems, either intentionally for a variety of purposes [4] or unintentionally [5]. Alien invasive species (e.g., the genera *Eucalyptus*, *Pinus,* or *Prosopis* species) are infamously known to degrade, exclude, and displace native species, as well as reduce their reproductive success [6,7]. Due to their numerous uses and socio-economic benefits, species such as *Moringa oleifera* Lam. (hereafter referred to as moringa) have been intentionally introduced to many parts of the world [8], including South Africa [9,10]. Its primary uses include human nutrition, human and veterinary medicine, livestock feed, biostimulant, bio-fertiliser, biodiesel, biogas, water purification, and cosmetics [11–13]. Plants with both high nutritional and medicinal properties, such as moringa, contribute significantly to human health in developing countries across the world [14]. For example, in some parts of Western Africa, moringa leaf powder is used in health projects to combat malnutrition among children [15,16]. Similarly, as national interest in the tree grows, various stakeholders in South Africa, including government departments, farmers, and higher education institutions, launched flagship projects centred on moringa [10]. Furthermore, Gomes et al. [17] emphasised the potential use of moringa leaf powder and extract as natural ingredients in the production of fortified foods that can be used to combat malnutrition.

Native to the sub-Himalayan parts of Northern India, *M. oleifera* Lam. belongs to the Moringaceae family and is the most widely used and well-known of the 13 moringa species [18]. Due to its commercial attributes, it is commonly referred to as the 'miracle tree', 'drumstick tree', 'horseradish tree', '*Makgonatšohle' (a Sepedi* word that means the ability to do everything), and 'mother's best friend' [19]. The plant is propagated through seeds or cuttings, with seeds planted directly in the field or seedlings raised in nurseries. Morphologically, it is a dicotyledonous, drought-tolerant, and fast-growing tree that can reach a height of 12 m at maturity [20]. The tree comprises tuberous taproots, and the stem is brittle, with cork bark that is whitish grey and drooping branches. Its leaves are pale green, bipinnate (or tripinnate), 30–60 cm long, with opposite and ovoid leaves [21] (Price 2007). The flowers are fragrant, bisexual, and zygomorphous, with five free petals that are oblong-spatulate, 1–2 cm long, unequal, white or cream, and finely veined. Moreover, the fruit is a pendulous and elongated capsule that turns dark brown in colour when ripe [22]. The tree grows mainly in tropical and subtropical regions with an annual rainfall of 250–1500 mm and a temperature range of 20–30 °C [21]. Moreover, it grows well in a wide range of soil types with a pH range of 5–9, though waterlogged soils may result in root rot [23]. Moringa is fast becoming an essential tree around the world due to its numerous uses, easy propagation, and wide ecological and climatic adaptability [11,12].

However, plants such as moringa, which are easily adaptable to a wide range of conditions, have the potential to spread extensively as invasive species, with widespread ecological and socio-economic consequences [24,25]. Although moringa has the potential to become invasive because of its life history and biology, several contradictory reports exist as to its invasive status globally. For example, others suggest that the species is detrimental to native ecosystems [26,27], while some suggest the risk of invasion is low [28], and others suggest the species is an important cultivated crop with no adverse effects posed to native ecosystems [29]. These contradictory perceptions and listings differ by locality, and exactly how the species may impact local ecosystems in South Africa is still unknown.

Currently, moringa is listed as a Species Under Surveillance for Possible Eradication or Containment Targets (SUSPECT) under the South African National Environmental Management Biodiversity Act (NEM:BA) regulation [30]. Most species listed in this category are considered invasive because of their noticeable adverse impacts on the ecosystem in South Africa [31]. Recently, contrasting views and conflicts have emerged regarding the control or management of biological invasions [7,32]. Considering the potential benefits of moringa and the implications of listing it under NEM:BA for eradication or control, this can cause conflict between communities that utilise the plant for health and economic gain and policymakers who are assigned to safeguard against adverse impacts triggered by alien species [13,31].

Dickie et al. [33] defined a conflict "*as a failure to account for, assess, and balance trade-offs among these ecosystem services or, at times, a failure to agree on the relative value of particular services*". According to Novoa et al. [34], conflict-generating species are alien invasive species that can provide significant societal benefits while negatively impacting ecosystem services. Conflicts concerning the management of invasive species can be divided into various dimensions or types. Young et al. [35] identified six major types or dimensions of conflicts: i) conflicts of interest; ii) conflicts over beliefs and values; iii) conflicts over information; iv) conflicts over process; v) structural conflicts; and vi) inter-personal conflicts. According to Zengeya et al. [32], most conflicts in South Africa concerning invasive species management can be described by multiple value systems (intrinsic vs. utilitarian) and cognitive levels (value systems vs. risk perception). Consequently, when a species is associated with both intrinsic and economic values, different types of conflict can simultaneously occur. Moreover, conflicts based on value are naturally difficult to resolve since policymakers ought to balance the needs of various stakeholders while ensuring conservation of the environment and ecosystem services. However, conflicts based on risk perception are primarily motivated by fear and aversion to the invasive species' impacts or the proposed management methods [36]. This is because human attitudes and behaviours towards the use and management of conflict-generating species, such as moringa, are mainly influenced by people's socio-demographics and knowledge about such species [37]. As such, the dimensions of conflicts and the options for resolving them can be highly taxonomic and region-specific.

A perfect management plan is one in which parties with opposing value systems reach an agreement on a win-win solution in which invasive species can still provide benefits [32]. This can be accomplished through open dialogue among stakeholders, trade-offs, and compromises. Indeed, stakeholder engagement is widely advocated for integrating diverse knowledge and perspectives in invasive species management, conducting risk assessments, and addressing potential [6] (Shackleton et al., 2019a). Stakeholder engagement, for example, has resulted in successful co-management of invasive mink (*Neovison vison*) in Scotland [38], reduced conflicts of interest, and improved consensus in South Africa regarding the management of invasive cacti species [34]. Without a proper risk assessment, it is difficult to justify listing a species such as moringa in the regulations, especially under a category where propagation and use of the plant may be prohibited [30]. Thus, it is imperative to consider the consequences and conflicts that may arise from listing moringa in the regulation without conducting a risk assessment and stakeholder engagement.

Currently, moringa is produced in all five district municipalities of the Limpopo Province (South Africa), and farmers have devoted an area of 0.25 ha or more for its cultivation [39]. Though moringa is reportedly produced in six provinces of South Africa [40], its prospective cultivation in all nine provinces was recently predicted by Tshabalala et al. [41] using Integrated Analytical Hierarchical Process (AHP) models. However, should moringa be allocated an impact category that leads to its eradication or restriction, its production may be halted, which in turn may impact the economic development and livelihoods of communities reliant on this species. This is because several issues concerning its social, economic, and ecological aspects within South Africa are still unknown, and there is little empirical evidence to substantiate listing moringa for eradication or control [31].

1.1. Complex system (socio-economic and ecological dynamics)

Challenges and issues related to the management of biological invasions are multiple and complex in nature [37,42,43]. The status of moringa in South Africa forms part of a highly complex social, ecological, and economic system. To help address these, there is a need to equip policymakers, researchers, communities, and relevant stakeholders with a new way of thinking beyond the traditional linear approach to solving problems and making informed decisions. Although traditional linear approaches play a role in solving problems by breaking them down into separate elements, complex issues require approaches that highlight and address problems through integrative methods as well as the inclusion of multiple perspectives [44]. Thus, a holistic, systems thinking approach may amplify the dynamics (i.e., cause and effect across scales) and assess the interconnectedness of various drivers of moringa, as well as aid in identifying any potential conflict associated with the species in the South African context.

1.2. Why systems thinking?

Banson et al. [45] defined systems thinking as a "*scientific approach involving the art of interconnected thinking and a set of tools to deal with complexity, ambiguity, and the integration of mental models into systems structures*". It is a corpus of knowledge built on an understanding of inter-relationships and emergent behaviours [46]. This approach affords a 'new way of thinking' to understand and manage complex issues [47,48]. It is predominantly suitable for dealing with societal and environmental issues because it provides a framework for managing complexity through the understanding of dynamic feedback entrenched in complex systems [49]. The effective use of systems thinking as a common methodology has been evident in several fields and disciplines, including environmental conflict management, agricultural production systems, natural resource management, decision-making, human resource management, and community development [49,50]. As such, this approach provides a mutual language for various stakeholders for deep discourse and consensus building [51].

Systems thinking accepts that a change in an area of a system component can negatively or positively affect another part of the system. Thus, encouraging self-organisation and development at all levels to avoid the silo effect [42,52]. This approach may contribute to resolving the conflict associated with moringa in South Africa since it allows decision-makers to avoid the consequences of policies and strategies as well as anticipate the long-term results of their decisions [49]. Systems thinking would therefore not only have a high potential for application in evaluating moringa production in South Africa but could also be used in the assessment of other conflict-generating species listed as SUSPECT under NEM:BA regulations.

There are four interrelated levels of systems thinking described by Ref. [53]: events or symptoms, patterns of behaviour, systemic structure, and mental models. The systems thinking paradigm and methodology embrace these four levels and provide a systemic framework to address complex issues [42]. Moreover, there are five key interconnected steps in a systems thinking approach: Problem Structuring, Causal Loop Modelling, Dynamic Modelling, Scenario Planning and Modelling, and Implementation and Organisation Learning [53,54]. It is important to note that each systems intervention does not necessitate undertaking all the steps [53]. Our study adopted the first two steps to develop a conceptual systems model that may aid in understanding the moringa complexity in South Africa, namely Problem Structuring and Causal Loop Modelling. The other three steps are used mainly for computer modelling [55], which was not the focus and emphasis of this study.

1.2.1. Problem Structuring

Problem Structuring methods are suitable for issues with multiple actors, diverging perspectives, partially competing interests, significant intangibles, and perplexity [56,57]. Problem Structuring is the most significant step in systems thinking because it outlines the key issues for management and establishes the study's boundaries and limitations [53,55]. The current study is limited to assessing the socio-ecological, socio-cultural, and socio-economic costs and benefits associated with moringa to ascertain its potential to cause conflicts among various stakeholders. As such, the evaluation of the entire value chain of moringa in South Africa was not the focus of this study. Additionally, the development of a quantitative simulation model of moringa production was not within the scope of this paper. Problem Structuring comprises discussions with key stakeholders to point out problems and define their significance [42]. For example, this can be achieved by conducting stakeholder interviews, either by bringing them together or in separate groups for creative Problem Structuring [45].

1.2.2. Causal loop model building

The key purpose of this step is to develop a conceptual model, also known as Causal Loop Diagrams (CLDs). The CLDs are a combination of variables that are connected by important causal relationships that are representative of a real-world system and used to show cause-and-effect dynamics [45,58,59]. It is often the first step, a practical approach to modelling, that successively converts the complex components into an understandable structure [60,61]. Ford [62] described this tool of systems thinking as basically a diagram comprised of 'words and arrows', whereby 'words' indicate variables in the systems and the 'arrows' represent causal connections between variables. This approach helps the stakeholders conceptualise and understand interactions and behaviour patterns between all variables of the system [63]. For instance, variables may indicate an action, decision, or condition that can be influenced by other variables and vice versa [64], and they can be qualitative or quantitative [65]. The relationships between these variables, represented by arrows, can either be positive (+) or negative (−) [60]. Reinforcing (R) loops are positive feedback systems that occur when alterations result in an increase or decline [66]. On the other hand, balancing (B) loops denote equilibrium and occur when changes in the systems' elements are fed back, contrasting the original alteration and thus resulting in a countering effect [67].

In this paper, a systems model was developed for conceptualising the status of moringa in South Africa using systems thinking and tools such as CLDs to demonstrate its application and effectively address complex and conflicting issues associated with the production of moringa. This helped to address the system's complexity by gathering the "mental models" of all stakeholders involved [44,49]. The CLD enables policymakers to make informed decisions in managing potential conflicting issues that are dynamic in nature, such as the status of moringa in South Africa, through established effective communication and engagements that attempt to reduce marginalisation, thus minimising conflicts. It shows a visualisation of the cause-and-effect relationship between variables and reinforces and balances feedback loops [58,59]. To the authors' knowledge, there are currently limited applications of systems thinking available in the literature on aspects related to moringa [68]. Also, this is the first study that adopts a systems thinking approach to amplify complex issues and challenges related to moringa in South Africa from a local to a national scale or elsewhere in the world at a global scale. Application at a global scale would take into consideration the worldwide distribution of moringa as well as the assessment of conflict-generating species across multiple systems (i.e., social, ecological, and economic). Therefore, the aim of this paper was to use a systems thinking approach to highlight the socio-ecological and economic interactions and interrelationships surrounding moringa. This may help to identify and understand the potential conflict that may arise due to assigning moringa an impact category of conflict-generating species within South Africa.

2. Materials and methods

We used a case study approach, focusing on the Limpopo Province since the majority of moringa production, development, and utilisation have been reported in the area [9,10,39,41]. Nevertheless, the systems approach applied in this study, together with the main recommendations, are likely to be pertinent to communities across South Africa and elsewhere around the world.

2.1. Description of limpopo province

Limpopo is one of the nine South African provinces and lies between the latitudes 22°2′S and 25°4′S and the longitudes 26°4′E and 31°9′E [69], with an area of about 125 754 km^2 and the highest altitude of 2126 m [70]. The province is in the northernmost corner of South Africa, bordering Mozambique, Botswana, and Zimbabwe. On its southern edge, from west to east, Limpopo shares borders with these South African provinces: the Northwest, Gauteng, and Mpumalanga. The province is situated in a dry savannah sub-region characterised by open grassland with scattered trees and bushes and a subtropical climate [71]. The province is divided into five district municipalities, i.e., Capricorn, Mopani, Sekhukhune, Vhembe, and Waterberg [69]. Mostly rural, the province has a population of 5.9 million people, making it the country's fifth largest in terms of population size [72]. The province's poverty rate has risen from around 10% in 2011 to around 11.5% in 2016 [73]. All district municipalities saw increases in poverty headcounts between these years, except for Vhembe, which saw a slight decrease from 13.0% in 2011 to 12.8% in 2016 [73].

2.2. Climatic conditions of the province

The annual average temperature of about 24.6 °C is expected, with a minimum average of 18.9 °C in June and a maximum average of 28.2 °C in January [74]. Rainfall varies significantly between years [75], ranging from 200 mm in hot, dry areas to 1500 mm in high rainfall areas [71]. Most of the rain falls in the summer months between October and March [71]. Subsequently, summer has a high number of sunny hours characterised by occasional afternoon thunderstorms [69]. Generally, the Southern Africa region is inclined to an incidence of droughts and floods, and the panorama for Limpopo Province is not different [74].

2.3. Agriculture in the province

Limpopo's agriculture contributes 7.6% of GDP towards national agriculture [72] and is the second largest commercial agricultural employer (97 478 employees, or 12.9% of the national total) after the Western Cape Province (186 997, or 24.7%) [72]. The province's total agricultural area is estimated at 11.32 million ha [71]. Nationally, Limpopo is a major producer of fruits such as avocados, mangoes, papayas, and tomatoes [76]. Other fruits, including bananas, litchis, pineapples, oranges, and table grapes, are also produced on large scales [76]. Limpopo is the top producer of potatoes countrywide and also produces other field crops, including cotton, groundnuts, and maize [77]. The province contributes significantly at the national scale to the production of field crops such as grain sorghum (43%), dry beans (22%), sunflower (10%), wheat (7%), and soybeans (4%) [72].

2.4. Moringa production in the province

Moringa was introduced to the Limpopo Province as a cultivated crop in 2006 by the Lammangata Moringa Project, situated in Tooseng village [9]. Since then, the number of farmers and its production has been on the rise in various parts of this province [39,40,78]. Within South Africa, moringa is mainly produced in this province by farmers and households. The reported cultivation area in the whole province is more than 0.25 ha. The estimated annual enterprise income for the moringa farmers in the province was $13 000 USD with a production cost of about $7000 USD, which resulted in a gross margin of $6000 USD [39]. Moreover, the climatic and environmental predictions made by Tshabalala et al. [41] are congruent with the optimal and suitable conditions for moringa cultivation in most parts of the province (80.3%).

Production of moringa leaf and seed oil products such as soap, tablets, shampoo, body lotions, energy drinks, and tea bags is fast becoming available in informal local markets [10]. Though local demand for moringa products is increasing at a fast rate, moringa production is insufficient and unstable [39]. The price of moringa leaf powder and products is quantity-dependent; thus, the bigger the quantity the buyer requests, the lower the price, and vice versa [79]. The price range of moringa leaf powder ranged between $1 USD and $2.75 USD per 50 g. However, the price of other moringa products was unstable and depended on market demands as well as targeted buyers. For these reasons, it is not feasible to measure profit per hectare. Unreliable access to markets was identified as the main challenge faced by moringa farmers in the province [39,80].

2.5. Problem Structuring

Similar to the study by van Mai and To Ref. [55], several methods were used to elicit the issues or variables constituting the moringa status system in South Africa (Table 1). The primary data used in this conceptual model mainly came from first-hand information obtained from moringa farmers through telephonic interviews and field investigations, as well as questionnaires and face-to-face interviews with communities (stakeholders).

Firstly, the study authors conducted 17 in-depth interviews by telephone with moringa farmers in the Limpopo Province between September and October 2020. Participants were recruited only if they were actively farming moringa. As a result, participants were knowledgeable of the cultivation practices, production, and harvesting processes, as well as the economic aspects of moringa. Approval to conduct the telephonic interviews was received from Stellenbosch University's Research Ethics Committee (REC: 2018–7868) before collecting data to ensure that the research was conducted ethically. Telephonic interviews were carried out by making prior appointments with farmers to ensure confidentiality. Pre-interview telephone conversations with the farmers took place before the actual interview [81]. This was done to address participants' concerns, build rapport, create interest, and explain the interview style. All participants were emailed and/or mailed consent letters outlining their rights, data confidentiality, and anonymity (see supplementary materials, Appendix 1). The interviews lasted between 20 and 40 min and were audio-recorded (see supplementary materials, Appendix 2). The interviews were electronically transcribed and then stored on a password-protected and encrypted laptop. Transcribed interviews were read numerous times to detect socio-economic and crop production variables constituting moringa systems, which captured the main messages conveyed by moringa farmers [82]. These interviews helped generate insight into cultivation practices, production costs, crop management, and harvesting practices. Inter-reliability was assured with the study authors engaged in the thematic analysis [83].

Secondly, semi-structured questionnaires and follow-up interview schedules were used to conduct a survey of 106 participants who cultivated moringa in their yards or farms in all five districts of Limpopo Province. This survey helped provide data on awareness about moringa, indigenous knowledge on uses of moringa, knowledge about government legislation and alien invasive species, and feelings about moringa listing under NEM:BA regulations (see Ref. [13] for detailed procedures followed during surveys).

Thirdly, ecological surveys were conducted on four moringa farms in Limpopo Province (see Ref. [84]). This allowed us to assess the impact of moringa on invertebrate biodiversity, with a specific focus on ants. Ants were selected as they are a good indicator of ecosystem health and are responsive to changes in soil and other environmental factors [85]. This survey helped gather data on the species abundance and composition of ground-dwelling and flying insects in moringa and natural sites (see Ref. [84] for procedures followed during ecological surveys).

Fourthly, two independent trials were conducted at the Welgevallen Experimental Farm (Stellenbosch University, South Africa). This was done to develop suitable concentrations of fertiliser application as well as to assess the change in nutrient concentration of leaves across harvesting ages for optimum moringa plant growth, biomass, leaf yields, and quality (see Ref. [86] for detailed methodology used). These empirical trials also provided information on the contribution of moringa leaves to the recommended dietary allowance (RDA) at various harvesting ages.

Finally, the conceptual model was developed using information obtained from a comprehensive review of the literature on moringa and alien species, including research publications and government documents (gazettes). For example, search words such as "moringa", "alien", "invasive", "NEM:BA", "climate", "moringa production", conflict-generating species", "biodiversity", "socio-economic", "Limpopo Province", "community", "temperature", and "fertiliser" were entered into the ISI Web of Science and Google Scholar. All the sources were then sorted and organised for relevance, and only those within the focus of the study were used. These were used together with the collected data to identify several key variables in the production and overall status of moringa in South Africa. The variables related to moringa systems in South Africa are shown in Table 1 and were all assumed to have equal weighting. Variables were organised into five clusters, i.e., social aspects, ecology, climate, economy, and crop production. These variables were then used

Table 1
Variables constituting the moringa system in South Africa.

Cluster	Variable	Definition	Reference/source
Social aspects	Awareness and familiarity	Hearing about moringa by rural communities from various sources such as family/community members, extension offices, farmers, internet etc. Also, the duration of knowing moringa in years.	[13]
	Cultivation of moringa	The practice of preparing and improving the land to grow moringa.	[13]
	Uses of moringa	Utilisation of moringa for purposes of food, medicine, livestock feed, shade and in production of cosmetic products by communities.	[13]
	Population	Similarities or differences in moringa use between males and females as well as between various age groups.	[13,87]
	Government policies	South African government policies and legislations that guide management of biological invasions countrywide.	[32]
	Perception	Aversion and concerns caused by rural communities of Limpopo Province due to moringa listing.	[13]
	DST	Involvement of South African Department of Science and Technology (DST) (now known as DHEST: Department of Higher Education, Science and Technology) in moringa production.	[88,89]
	DAFF	Involvement of South African Department of Agriculture, Forestry and Fisheries (DAFF) (now known as DALRRD: Department of Agriculture, Land Reform and Rural Development) in moringa production.	[40,78]
	DEA	Department of Environmental Affairs (DEA) (now known as DEFF: Department of Environment, Forestry and Fisheries) listed moringa on Species Under Surveillance for Possible Eradication or Containment Target in the status report of biological invasions.	[30]
	ARC-VOP	Involvement of Agricultural Research Council−Vegetable and Ornamental Plants (ARC−VOP) in numerous moringa-related activities.	[90]; https://www.arc.agric.za/arc-vopi/Pages/Crop%20Science/Medicinal-Plants.aspx
	ARC-PPRI	Contributions of Agricultural Research Council−Plant Protection Research Institute (ARC−PPRI) (now known as ARC−PHP: Plant Health and Protection) on the status report in which moringa is listed as SUSPECT.	[30]
Ecology	Ant abundance	The impact of moringa on ant abundance in moringa orchards versus natural sites.	[84]
	Ant diversity	The impact of moringa on ant species diversity in moringa orchards versus natural sites.	[84]
	Other insects' abundance	The impact of moringa on other insects' abundance in moringa orchards versus natural sites.	[84]
	Biodiversity	The impact of moringa on biodiversity of native species.	[84]
	Alien invasive species	Species that occur outside their natural range and dispersal potential. In the context of this study, moringa is an introduced plant species to South Africa.	[30]
	Soil quality	Soil requirements ideal for moringa growth.	[91]
	Pests	A damaging and noxious living organism that does not include bacteria, fungus, virus or internal parasites. It includes insects, plant pathogens, birds, weeds, non-human mammals and other organisms which do not cause medical complications to humans.	Socio-economic surveys
	Pest management	It is a process by which information is collected and used to make good management decisions to reduce pest population impacts in a planned coordinated way.	Socio-economic surveys
Climate	Temperature	The ideal temperature regime suitable for moringa growth.	[92]
	Rainfall	The amount of rainfall required per annum for successful moringa production.	[21]
Economy	Income	The sum of money or its equivalent received by farmers during harvest per ha/tree.	Socio-economic surveys [39];
	Crop yields	The amount of a moringa crop harvested per ha/tree.	Socio-economic surveys [39];
	Crop production costs	The sum of money spent by farmers on ensuring the successful production of moringa.	[39]

(*continued on next page*)

Table 1 (*continued*)

	Crop labour	The sum of money farmers spends on paying labour force on moringa production.	Socio-economic surveys
	Access to market	The ability and opportunities to sell moringa leaf powder and products across borders. It includes domestic and international trade.	Socio-economic surveys
	GDP	Gross Domestic Product (GDP) is the monetary value of all finished goods and services made within a country during a specific period.	[73]
Crop Production	Harvesting age	Different harvesting age affect the plant growth, yield and nutrient composition of moringa.	Experimental data [86]
	Fertiliser requirement	The amount of fertiliser application required for successful moringa production.	Socio-economic surveys
	Above-ground biomass	The effects of fertiliser levels on dry shoot mass of moringa.	Experimental data [86]
	Root biomass	The effects of fertiliser levels on the amount of dry root mass produced per tree.	Experimental data [86]
	Stem biomass	The effects of fertiliser levels on the amount of stem mass produced per tree.	Experimental data [86]
	Leaf biomass	The effect of fertiliser levels on the amount of leaves produced per tree.	Experimental data [86]
	Nutrient content	The amount of essential nutrient found in moringa leaves.	Experimental data [86]
	Contributions to RDA	Nutritional content in moringa leaves contribute significantly to the recommended dietary allowance (RDA).	Experimental data [86]

to develop a CLD to understand the complex systemic structure of moringa.

2.6. Formulation of causal loop diagram of moringa production

The development of a CLD in this study went through four interconnected steps [93]. Vensim PLE 7.2 software was used to transfer the data to a digital format and visualise it in the form of a CLD. Firstly, the key moringa drivers and impacts (i.e., variables) were identified from primary data and relevant literature reviews on moringa and alien species publications and government documents (Table 1). Secondly, these variables were used to develop a preliminary CLD. Thirdly, the core elements of the preliminary CLD were then shared with several academic and industrial personnel with expertise in moringa, biological invasions, and modelling for critical feedback, which was used to produce a working CLD. Lastly, the working CLD was reviewed, and inconsistencies or errors identified in the model were addressed to produce the final version (Fig. 1).

3. Results and discussion

In Fig. 1 below, we see that the potential conflict related to moringa can be conceptualised as a group of stakeholders with different values [61]. Here, we observe that one stakeholder group advocates for the production and utilisation of moringa, while another group views it as a species that should be targeted for eradication or control. This brings the values being pursued by the two groups into conflict. The CLD allows visualisation and capture of variable interactions with reinforcing and balancing characteristics to identify feedback loops [55]. This is shown here within the holistic system of the status of moringa in South Africa since it demonstrates several direct and indirect connections between variables inside and outside the system as well as feedback loops [59]. Within the system outcomes, there are seven reinforcing feedback loops (Fig. 1): the socio-cultural impact of listing moringa loops (R1 and R2), the ecological impact of moringa on biodiversity loops (R3, R4, and R5), the crop yield loop (R6), and the fertiliser requirements loop (R7). These seven loops are described below.

3.1. Socio-cultural impact of listing of moringa feedback loops (R1 and R2)

Individual or group demographics and knowledge, as well as species properties, heavily influence human attitudes and behaviours towards the use and management of conflict-generating species [37,94]. According to Novoa et al. [34], studies that assess social

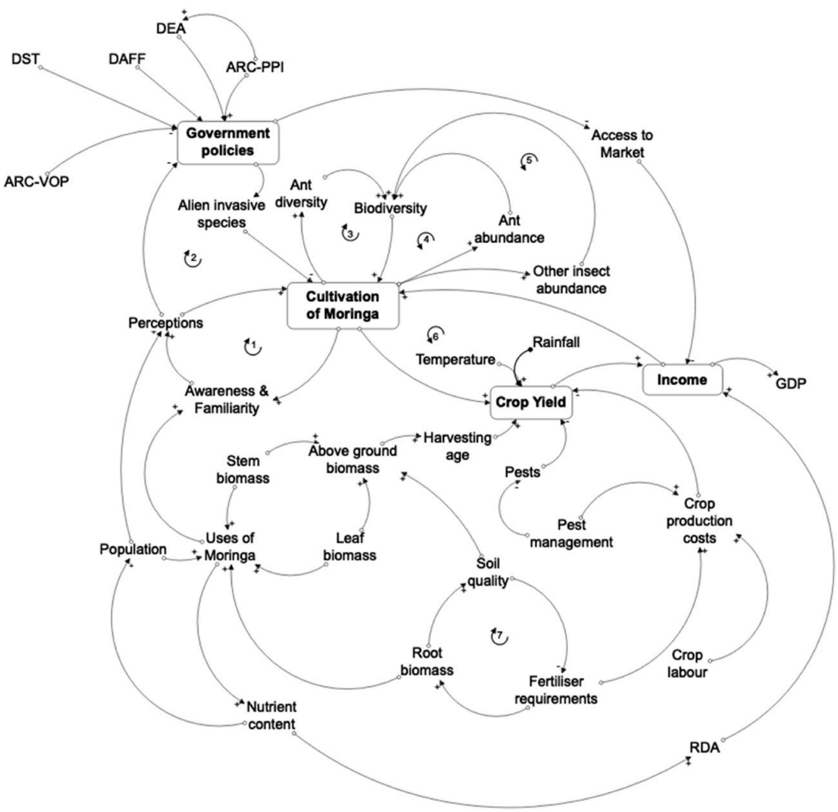

Fig. 1. Causal Loop Diagram of moringa status in South Africa. The arrow heads have polarity signs which indicate whether the relationship between variables is either increasing (+) or decreasing (−).

perceptions and the role that conflict-causing species play in societies are also important. Loop R1 highlights the role of awareness and familiarity with moringa in promoting its production and utilisation (Fig. 2). This loop contains variables of awareness and familiarity, perception, and cultivation of moringa. Loop R2 makes a link between variables of cultivation of moringa, awareness and familiarity, perception, government policies, and alien invasive species, and it depicts the effect of listing moringa as a SUSPECT under NEM:BA on its cultivation and uses (Fig. 2). Furthermore, the restrictions imposed by government policies on moringa as a potential invasive species will negatively affect its cultivation, and loop R2 shows that the consequences of assigning moringa an impact category would be felt directly by communities associated with moringa.

Results from surveys revealed that participants in rural communities in the Limpopo Province heard about moringa from family and/or community members, radio/TV, extension officers, and the internet [13]. Participants had known about moringa for more than a decade, but its popularity has been on the rise in the last five years. Moreover, participants were aware of and well informed about the multiple uses of moringa. Subsequently, it is regarded as an important tree used for nutrition in food, medicine for about 56 diseases and illnesses, skin health, livestock feed, shade, and an income source for farmers [13]. However, prior to participating in the study, many villagers (76%) had no knowledge about alien invasive species, their impact on the environment, or government policies that guide their control and management of biological invasions. When asked about their perception of the eradication or containment of moringa, many participants (78%) expressed their dissatisfaction and disappointment with either decision. Furthermore, they stated that their health and overall wellbeing would be greatly affected (see Ref. [13] for detailed results and discussion).

Although South Africa has legislation that guides the management of biological invasions, interventions are challenging to execute because of the importance of such species among communities [95]. As such, management interventions for targeted species such as moringa should be justified by means of an all-inclusive approach to avoid any potential disputes [31,37]. For example, some species, such as *Jacaranda mimosifolia* (jacaranda), were categorised as beneficial because they were perceived as iconic trees that formed part of the identity of the city of Pretoria (South Africa), despite their potential as invasive species [96]. The conflicts that arose during attempted management actions were resolved through engagements and compromises that involved regulating the species in the areas where they occur. As a result of this, jacaranda trees are not listed as invasive in certain areas in various provinces like Gauteng, Limpopo, North-West, and KwaZulu-Natal [32]. Moreover, Ellender et al. [97] reported that potential conflicts may emerge from management interventions of black bass species such as *Micropterus salmoides* and *M. dolomieu* that have been associated with negative impacts on environments and native biota while at the same time having significant economic benefits to communities. In the current study, loops R1 and R2 indicate that the cultivation of moringa, awareness and familiarity, and government policies are reinforcing. Clearly, loops R1 and R2 play a significant role in addressing the social issues associated with the cultivation and listing of moringa.

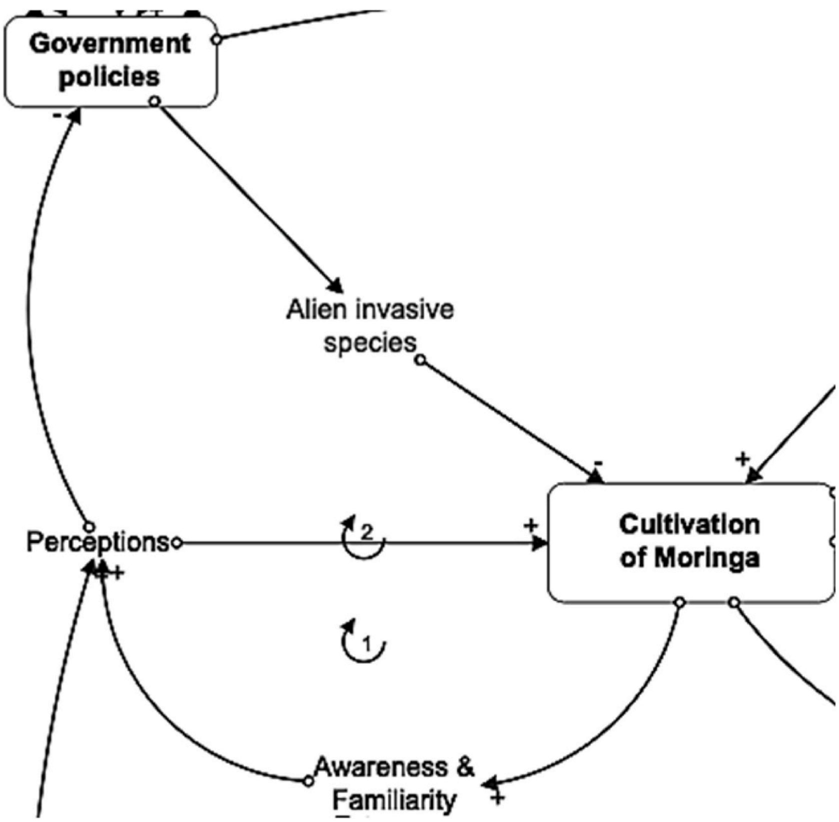

Fig. 2. Socio-cultural impact of listing moringa loops.

Indeed, improving the cultivation and uses of moringa helps to increase awareness and familiarity among communities; however, allocating moringa an impact category by the government may affect its cultivation.

Nationally, the production of moringa has attracted many government bodies and institutions due to its significant nutritional health benefits and growth adaptability to a wide variety of conditions [10,78,88]. With regards to government policies, the CLD in Fig. 1 shows that DAFF, together with DST, are promoting moringa production, utilisation, and commercialisation [40,78,88,89], while the DEA has placed moringa on the SUSPECT list under NEM:BA regulations [30]. There is already a conflict between the two departments, which indicates a lack of communication on legislation and mandates. Moreover, DAFF and DST are encouraging ARC-VOP to conduct studies that promote moringa production in South Africa (https://www.arc.agric.za/arc-vopi/Pages/Crop%20Science/Medicinal-Plants.aspx), while ARC Plant Protection Research Institute (ARC-PPRI) is one of the contributors to the status of biological invasions and their management report issued by the South African National Biodiversity Institute (SANBI) [30]. This implies that even within the ARC, there is disagreement between institutes, thus creating conflict, albeit probably unintentionally. Similarly, the lack of communication and trust between stakeholders and government agencies was also reported during an attempt to manage trout species, and this was caused by a lack of confidence in government authorities as well as a lack of community engagement and transparency in their decision-making [32]. Effective communication can achieve success in resolving these conflicts through interconnected thinking with all stakeholders, and this will help in decision-making regarding moringa as well as other issues that are dealt with by several government and private departments.

3.2. Ecological impact of moringa on biodiversity feedback loops (R3, R4 and R5)

Loops R3, R4, and R5 describe the ecological impact of moringa on species diversity (Fig. 3). Loop R3 links the variables of moringa cultivation, ant diversity, and biodiversity. It shows that the increase in moringa cultivation arrow on the ant diversity arrow improves the biodiversity arrow and, in turn, increases the cultivation of moringa. Loop R4 connects the variables of cultivation of moringa, ant abundance, and biodiversity, while loop R5 contains the variables of cultivation of moringa, other insects' abundance, and biodiversity (Fig. 3). According to Downey and Richardson [98], alien invasive plant species can change ecosystems by modifying native species composition and causing biodiversity loss. Though alien species are known to have adverse effects on ecosystem services, our ecological surveys defied this ideology with moringa [84].

The abundance and composition of the ground-dwelling and flying insects in moringa and natural sites were compared using pitfall traps and pan traps [84]. Using ants as an indicator group for ecosystem health, an equal distribution of some of the dominant and general ant species typical of the area was found. The abundance of ants in moringa stands suggests that the soil ecology is appropriate for them to survive, as they are responsive to changes in soil and other environmental factors [85]. The group of species found in moringa and natural sites was similar, suggesting that there were no losses in species diversity [84]. It was demonstrated that the presence of moringa trees only established an alternative type of suitable environment for numerous insects. Moreover, it was highlighted that moringa had no adverse impacts on arthropod richness and thus may not have a negative ecological impact on the environment [84]. These imply that the proposed listing of moringa [30] should be reconsidered, and its cultivation as well as uses should be the main emphasis, considering the numerous potential benefits linked with this crop. Loops R3, R4, and R5 indicate that ant abundance and diversity and the abundance of other insects were mutually reinforcing. That is, improving ant abundance and diversity as well as the abundance of other insects helps retain biodiversity, which would encourage farmers and rural communities to continue improving moringa cultivation. The connectedness of the variables of moringa cultivation, ant diversity and abundance, and other insects' abundance and biodiversity demonstrated improved insect biodiversity, indicating that the ecology of moringa sites is good for the improvement of biodiversity. The interconnectedness allows identifying the cause-and-effect relationships and dynamics between these variables at various spatial scales and domains [58]. Since moringa does not have negative effects on biodiversity and ecosystems, it would subsequently promote its cultivation among farmers and households in marginal communities.

3.3. Crop yield feedback loop (R6)

Since moringa production in South Africa is still in its infancy and developmental stage [39], it is challenging to estimate the areas

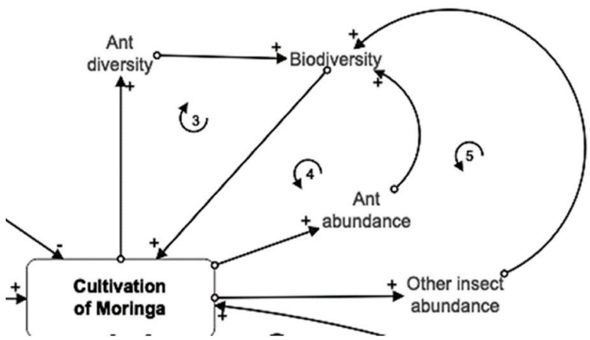

Fig. 3. Impact of moringa on biodiversity.

that are devoted to its cultivation [10]. Loop R6 describes the important role of moringa cultivation in improving the income of farmers in Limpopo Province. It makes a link between the variables of moringa cultivation, crop yield, and income (Fig. 4).

The telephonic interviews conducted in the current study revealed that moringa farmers in Limpopo Province propagated the crop from seeds and cuttings. Seeds were sown directly into the soil or by planting them first in seed trays, while transplanting was done when the seedlings were about one month old. Some farmers revealed that they soaked seeds in water a day before planting. It was mentioned that cuttings were the least successful method of propagating moringa. *Farmer H* gave the following response: *" … if you plant it using seeds, it will develop a very strong root system. But trees planted using cuttings are easily blown away by wind because they do not develop a long tap root system … "*. This corroborated the findings of Price [21], who revealed that trees cultivated from seeds developed longer roots for balancing and accessing water compared to those grown from cuttings, which have much shorter roots. As such, others Leone recommended that planting moringa using cuttings may be ideal when seeds are scarce and/or with sufficient labour [99].

Planting density differed for moringa leaf and seed production. For leaf production, planting density ranged between 500 and 100 000 plants. ha^{-1}, using compacted inter- and intra-row spacing (i.e., 10 cm × 10 cm; 50 cm × 50 cm; 50 cm × 100 cm). These responses were in line with the study by Leone et al. [99], who suggested that moringa plantations should be designed with spacing of 10 cm × 10 cm or 20 cm × 20 cm for intensive leaf production. Gadzirayi et al. [100] demonstrated that closer plant spacing (i.e., 15 cm × 15 cm) produced high biomass production. In addition, some reported a high plant population per unit area with closer spacing, which produced vigorous rooting and higher crop yields [101].

During surveys, farmers mentioned that the first harvest of moringa leaves may be done when the trees are about 1–2 m in height (i.e., 3 − 4 months old) and are cut off from 30 cm above the ground. The leaves were harvested 4 − 9 times in a year, depending on the size and age of the trees as well as demand. The following response *(Farmer B)* was given: *"Normally I take about one year before I can harvest the leaves. You can still harvest the leaves within less than nine months, but if you do so, you will be retarding the potential growth of the plant … "*. Comparable to the current study, others deduced that the green matter may be harvested when the plants reach a height of at least 50 cm above ground and subsequently after every 35 − 40 days [102]. However, it was also pointed out that harvesting moringa was habitually done when necessary, and this may be justification for their failure to measure the total leaf yield production. Seed harvesting was done once the trees were at least one year old. After the initial harvest, the next harvest was done every six months. This was confirmed by Paliwal et al. [103], which reported that moringa branches develop new pods within six months after pruning. According to Leone et al. [99], early flowering varieties of moringa produce pods at six months, while other varieties require at least one year. Thus, the amount of crop yield needed to generate a satisfactory farmer's income depends on many factors, such as planting season, rainfall, temperature, plant density, age of the plant, and other crop management practices.

Though moringa was planted in all seasons, farmers stated that the growth and yield decreased in the winter. *Farmer A* was quoted as saying, *" … during winter, it is a little bit slower for the plant to grow, but in the summer, it is very hot and is growing very fast. In winter, it takes almost two weeks longer than normal"*. It was mentioned that during the summer, farmers relied on rainfall for irrigation, and in the winter, the trees were only irrigated once every two weeks. Drip and flood (i.e., using buckets and hose pipes) irrigation were applied at least once and at most three times a week during the early stages of growth. Once the trees were well established, irrigation was done once every 2 − 4 weeks (applying about 4–5 L per tree). Among all climatic factors that influence plant growth, temperature and rainfall are the most important factors governing natural plant distribution, tree performance, physiology, and productivity [104]. Irrigation is a vital factor for attaining optimum yields from field crops such as moringa in South African areas of very low rainfall [75]. However, it is important to note that moringa is a highly radiation-efficient crop and has the capacity to produce a satisfactory crop yield in low-rainfall tropical and subtropical regions. Loop R6 indicates that the crop yield is reciprocally reinforcing (Fig. 4). This loop highlighted the significant role of improved cultivation practices in increasing moringa crop yield and the income of farmers in Limpopo Province. That is, improved cultivation of moringa leads to better crop yield. The better crop yield increases farmers' income, which also leads to more moringa cultivation. Through the systemic approach, one can assess the likely outcomes of diverse systemic interventions by viewing what would happen to the whole system when a certain strategy or decision is executed [105].

Although investigating pests was not within the scope of this study, some farmers observed that the yield and quality of moringa produce were affected by pests. Farmers mentioned that black 1 cm 'small boll worms' were the main moringa pests. The worm infested the moringa orchard and fed on leaves during the summer. One participant gave the following response: *"There was this small black-like worm that was coming in around October. The small boll worms were eating moringa leaves rapidly. There were lots of them; maybe 50 to 100 on one tree"* (*Farmer G*). Farmers applied pesticides (i.e., DiPel DF) monthly to manage the infestation of small bollworm. However, some said that due to organic farming practices, pesticides were not applied to their moringa fields; thus, leaf harvesting was

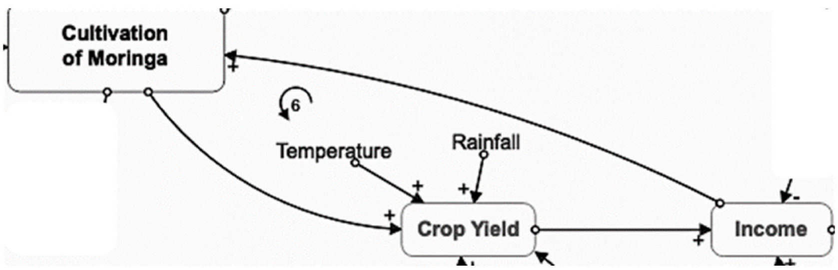

Fig. 4. Crop yield loop.

done immediately after scouting infestations. One participant (*Farmer B*) stated that "*Since we are practicing organic farming, we do not use pesticides. We just harvest quickly when we see the worms … "*, which helped regulate pest damage and contributed to increased moringa leaf yield. Also, it was mentioned that the outbreak of fall armyworms two years ago affected their yields. It was stated that moringa leaves were further attacked by red spider mites and birds. Several studies reported that moringa seedlings were often infested and attacked by spider mites (*Tetranychus urticae*), which caused withering and subsequent death [106]. The CLD (Fig. 1) shows that pests have a negative impact on crop yield and may be reduced by good pest management strategies. Management of pests is one of the essential measures in agriculture for guaranteeing high yields and the quality of the produce [107]. Indeed, it is important to assess the seasonal occurrence of these pests and the nature of damage they cause [108], as this would assist with effective management control measures at certain seasons.

3.4. Fertiliser requirements feedback loop (R7)

Loop R7 depicts the fertiliser requirements for improving the biomass of moringa crops. It comprises the variables of fertiliser requirements, root biomass, and soil quality (Fig. 5). Loop R7 shows that improved soil quality reduces fertiliser requirements, which would in turn improve the root biomass. Although farmers indicated that they mainly harvest the leaves and seeds, improved soil quality may also increase other yield parameters (i.e., stems and roots). Farmers applied compost, cattle and chicken manure, phosphate, and nitrogen fertilisers once, mostly during planting and/or early seedling growth. The amount applied ranged between 150 and 160 kg ha^{-1}. Some farmers indicated that they did not apply any type of fertiliser for moringa production. *Farmer H* said: "*We do not encourage people to use any artificial (chemical) fertilisers because it compromises the purity of the plant. We would rather use kraal or chicken manure because it is organic … "*. Likewise, Mabapa et al. [39] revealed that moringa farmers in Limpopo Province used both organic and inorganic fertilisers to improve growth, whereas some cultivated it under natural conditions. Similarly, the use of kraal manure and composts on crops such as moringa was reported by Rankoana [109] in Mogalakwena community, Limpopo Province, for improving soil fertility and structure. This helped to achieve sustainable crop production and organic farming practices, as well as reduce the cost of crop production. Furthermore, experimental trials conducted by Dania et al. [110] showed that the application of poultry manure significantly increased the vegetative growth of moringa. However, Marcu [22] argued that moringa requires less fertiliser and can thrive in marginal soils. Our greenhouse trials also showed that various rock dust (RD) and nitrogen, phosphorus, and potassium (NPK) fertiliser levels did not have any effect on growth, yields, root biomass, or above-ground biomass. Moreover, it was suggested that moringa grew well with little or no synthetic fertiliser application (see Ref. [86] for detailed results and discussion).

Loop R7 indicates that the root biomass is reinforcing. That is, high soil quality helps reduce fertiliser requirements, and vice versa. This would potentially lead to a reduction in production costs and a subsequent increase in above-ground biomass and yield. Soil quality is one of the key factors that contribute to successful and optimum crop productivity and may be improved by the application of organic and inorganic fertilisers [91]. Thus, additional fertilisation is essential for optimal yields and plant survival.

3.5. Role of stakeholders on decisions regarding moringa status

The conflict of interests between stakeholders surrounding the management of invasive species occurs due to trade-offs between costs and benefits surrounding economic, social, and environmental factors as well as intrinsic issues [32,34]. Moshobane et al. [111] identified the public's opposition as one of the major challenges encountered by the generator of lists. For instance, the listing of plant taxa such as *Jacaranda mimosifolia*, Cacti species, and some Acacia species resulted in conflicts of interest between stakeholders [33, 34]. This is because the listing of certain taxa on the NEM:BA alien invasive species list was purely based on experts' opinions, and many other stakeholders with alternative understandings and world views to these experts were not consulted [111]. Also, the process of listing moringa as a SUSPECT under NEM:BA was done without effective stakeholder engagement or prior cost-benefit assessment [31]. Indeed, regulatory measures targeted at species such as moringa trigger public responses based on societal values in South Africa and elsewhere. This shows the necessity to better understand perceptions, knowledge, and public views and design proper engagement and awareness campaigns [6,7].

Problem solving becomes a challenge since different stakeholders bring diverse perceptions to bear. That is, one stakeholder's improvement may be a setback for another [57,105]. For instance, rural communities and DAFF view moringa as a beneficial

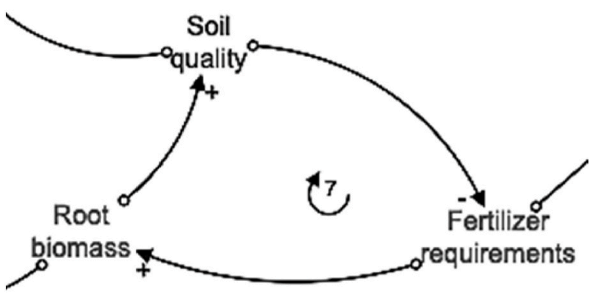

Fig. 5. Fertiliser requirements loop.

multifunctional tree that can be used to alleviate malnutrition and poverty, whereas government bodies such as DEA regard it as a SUSPECT that may disrupt ecosystem function and services. According to Friend and Hickling [112] and Sydelko et al. [113], the use of traditional approaches in problem solving can lead to unintended adverse outcomes due to interactions with other issues and decisions. These happen because traditional approaches often and unknowingly lean towards one perspective, and in doing so, other stakeholders' perspectives are marginalised, thus resulting in conflicts [49]. In the case of moringa, policymakers may prefer its legal status over its potential benefits, and this will halt moringa cultivation and distribution.

Consultancy with all stakeholders (i.e., farmers, communities, scientists, and environmental experts) brings different solution anchors to decision-making on assigning moringa an impact category that will favour its production and distribution [46]. Actions that aim at managing species that have both benefits and 'negative' impacts (i.e., *Prosopis* species) are often complicated and cause conflicts around their benefits and/or the harm they impose on the inhabitant ecosystems [32,43]. Previous attempts to control species such as *Jacaranda mimosifolia* that were categorised as beneficial but not harmful also led to conflicts in Pretoria (South Africa), which were resolved through stakeholder engagements and compromises that included regulation of the species by area [33]. Likewise, compromises in regulation by area have also been made for listed plant species such as *Eucalyptus cladocalyx*, *E. diversicolor,* and *E. grandis* [114]. According to van Wilgen and Richardson [37] and Novoa et al. [34], the dimensions of rising conflicts of interest around species such as moringa and the options that exist for resolving these conflicts can be region-specific and influenced by the properties of species. This should be done in the case of moringa because stakeholders such as farmers and rural inhabitants regard moringa as an important multifunctional food crop [13]. Also, ecological studies conducted in South Africa [84] and elsewhere [28,29] indicated that this species does not have negative impacts on the environment and has a low chance of spreading outside cultivation or homesteads.

In this study, the impact assessment of the alien species moringa, on agroecosystems and society was conducted using a systems thinking tool, i.e., CLD, to provide a comprehension of the dynamics and interconnected linkages that exist within agricultural systems, resulting in smart, sophisticated adaptive management. The involvement of stakeholders greatly increases the likelihood of an assessment of the conflict associated with moringa. In addition, using methods and tools such as systems thinking in identifying potential conflicts may encourage thorough engagement, reflection, and learning among participating stakeholders and subsequently promote continual adjustment within the system dynamics [115]. The CLD presents the important variables of the status of moringa in South Africa as well as the interactions that affect what happens, and it models those interactions to identify the underlying causes of system behaviour. The CLD demonstrated the impact of qualitative variables such as 'government policy' and its chain effects on other key outcomes. It was found that the current listing of moringa on the national status report of biological invasions can be traced back to a lack of effective communication between government departments, therefore leading to undesirable outcomes. Furthermore, it was demonstrated that variables or factors that affect a system are not independent but are connected dynamically and cause an increase or decline in each other.

The challenges concerning the complexity of moringa's status in South Africa require the use of systems thinking to provide stakeholders with tools to assess interconnections between variables, consider diverse perceptions of various stakeholders, and resolve potential conflict associated with its production [49,54,64]. Similarly, Ufua et al. [116] used systems thinking to assess the intrinsic conflicts among Nigerian public security forces and concluded that this approach can afford a project-based public security service delivery established on effective communication and engagements that attempt to reduce marginalisation, thus minimising conflicts. As such, the CLD developed here will enable decision makers to be well adaptive and informed in managing potential conflicting issues that are by nature dynamic, such as the status of moringa in South Africa.

4. Conclusion and recommendations

The status of moringa in South Africa is a complex problem due to different perceptions of its value among various stakeholders (i.e., government bodies, farmers, societies, and researchers). For government bodies such as the DEA, moringa is viewed as a potential invasive species that can disrupt ecosystem function and services. Subsequently, its legal status may halt its cultivation and distribution. In contrast, our ecological surveys and literature, based in South Africa as well as other parts of the world, showed no adverse environmental impacts associated with the presence of moringa. Also, DAFF and DST policies and measures have been designed to promote the production and utilisation of moringa in South Africa. This has led to the national establishment of moringa projects and activities, mainly in Limpopo Province. Although moringa is a non-native species to South Africa, many of its uses are known by societies, and its cultivation is on the rise in many parts of the country. Nevertheless, listing moringa as a SUSPECT under NEM:BA raises many uncertainties among stakeholders. The listing of moringa has mainly focused on addressing its environmental impact (i.e., listing was based on records of its occurrence outside cultivation at one locality in the Limpopo Province) while neglecting the interconnectedness of the system components.

Through a systems thinking approach, we developed a CLD to provide an understanding of the complexity of moringa production in South Africa. The CLD helped in highlighting the feedback mechanisms within the moringa system. Furthermore, the CLD showed that the status of moringa comprises various interdependent variables of socio-cultural systems, government policies, the environment, and the economy, which are intertwined into a complex system. That is, alterations in one variable will influence the other variables, subsequently affecting the entire system. In addition, the CLD helped capture the key driving forces that affect present and future developments in moringa production. This can consequently offer a useful platform for communication, consultation, dialogue, collaboration, and decision-making among stakeholders, thus avoiding any potential conflicts. The CLD can also assist policymakers in tackling the root causes of challenges linked to moringa instead of simply treating the symptoms. This is because it enables policymakers to devise appropriate intervention strategies that can help manage moringa cultivation and potential spread more effectively.

We recommend that the application of a systems thinking approach through the construction of a CLD can afford a broad understanding of the moringa system's complexity. It can therefore serve as a useful tool for engagement and decision-making among stakeholders involved in the legal and social status of moringa in South Africa. Furthermore, the development of regulatory lists on alien and invasive species across the globe (particularly conflict-generating species) should be guided by empirical-based information in an unbiased and transparent process. This would improve future listing processes and justify management interventions, especially for other targeted conflict-generating species around the world.

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Ethical approval

The study complied with the Stellenbosch University's policy on research ethics and permission was received from the University's Research Ethics Committee (REC: 2018–7868) prior to data collection to ensure that the research was ethically conducted. Stellenbosch University policies, appropriate legal framework and ethical considerations were adhered to during and beyond completion of this study. All participants provided informed consent to participate in the study.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Chuene Victor Mashamaite: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ethel Emmarantia Phiri:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tonderai Clive Mandizvidza:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis. **Palesa Natasha Mothapo:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Petrus Jacobus Pieterse:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Anouk Jasmine Albien:** Writing – review & editing, Visualization, Validation, Supervision, Methodology.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e26906.

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