The promotion of amaranth value chains for livelihood enhancement in East Africa: A systems modelling approach

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Abstract

This paper conducts ex-ante impact assessments for policy interventions to promote amaranth value chains in Tanzania and Kenya. Amaranth is an underdeveloped, drought-resistant, and nutrition-rich crop used for human food, animal fodder, and ornamental purposes. Promoting amaranth value chains is a difficult task, given that amaranth is not a well-established commodity and has limited market outlets in the developing world at present. This paper provides a framework within which conduct scenario analysis of ways to promote amaranth value chains using system dynamics (SD). We constructed an integrated amaranth production and market model to evaluate the impact of producer adoption of improved production technologies (improved seed varieties), and changes in demand for amaranth products, on producer profits and planting behaviour. The results of our model show that the profitably upgrading and commercialising of amaranth value chains require multi-faceted and chain-level interventions that improve supply- and demand-side conditions. Interventions that target only the supply side serve to increase amaranth production, but generate minor economic gain for producers.

Key words: amaranth; East Africa; Tanzania; value chains; system dynamics

1. Introduction

Food security remains a crucial issue in many parts of the developing world. This has focused agronomic, production and economic research on the promotion and improvement of staple crops such as rice, wheat and maize. However, in many contexts, such as sub-Saharan Africa, the production of these important staples is increasingly compromised by a reliance on climate change-sensitive variables, including rainfall and soil conditions (National Academy of Science 1975; Venskutonis & Kraujalis 2013). Identifying alternative staple crops that are more resilient to climate change but still provide food security consequently is an important area of research inquiry.

Amaranth is an example of such a crop. It is a fast-growing, resilient and nutritious crop that requires substantially less water to grow than do other staples such as maize (Bjarklev *et al*. 2008). Both leaves and seeds provide rich sources of micro- and macro-nutrients. An extensive literature exists on amaranth genetics, agronomy, processing, nutrition and income-generating profile (Achigan-Dako *et al*. 2014; Chagomoka *et al*. 2014; Ebert 2014; Njoki 2015; Krulj *et al*. 2016; Kyagulanyi *et al*. 2016; Schröter *et al*. 2018; Rybicka *et al*. 2019). However, the commercial potential of amaranth and its role in food security have not been researched. Producer adoption of improved varieties, the nature of the market and market influences on producer behaviour all remain unknown. Similarly, influences throughout the supply chain, such as new technology uptake and product promotion, or an in-depth understanding of the supply chain itself, have not been studied or are not available.

For producers, amaranth's viability in adverse soil and climatic conditions (Achigan-Dako *et al*. 2014; Kyagulanyi *et al*. 2016) makes it attractive, particularly on marginal lands. Markets for amaranth-based products, whether local or global, are not well established, however, particularly in the developing world. High prices relative to maize and wheat make it more expensive for processors like bakeries to adopt amaranth as an input to production. Niche marketing is one potential response, alongside targeting suitable producers, but such strategies or potential outlets have not been assessed for viability. Commercialising amaranth production successfully will require a coordinated focus that minimises the risks of chain failure. Chain failure is an adapted form of externality (sub-optimal performance of the chain because of the presence of system externalities) occurring within the supply or value chain. Primarily applied to agricultural value chains that do not lend themselves to conventionally defined market interventions (Griffith *et al*. 2015; Baker *et al*. 2017), chain failures have been shown to be best addressed by an industry or supply-chain approach (Baker *et al*. 2017).

This paper examines the likely contribution of amaranth in enhancing food security in dry regions and the commercialisation potential of amaranth from a supply chain perspective. The former has been addressed through a literature review (see section 2: Amaranth) on the nutritional characteristics of amaranth and its ability to grow in adverse environmental conditions, while the latter has been addressed by measuring the likely profit (measured by subtracting cost from revenue) of producers under different scenarios. A novel aspect of this paper is the development of a quantitative simulation model that enables scenario analysis for the amaranth value chain. Our scenarios examine the interactions amongst policy-relevant changes such as the effects of producer adoption of improved varieties, changes in market demand, and production and producer profits. These models are assembled and calibrated on the basis of primary data at the levels of the producer and raw amaranth trading (unprocessed amaranth leaf). Although our model focuses on amaranth production by smallholder farmers, with appropriate adjustments, the model developed here can be applied to other regional and commodity contexts.

2. Amaranth

Amaranth is a multipurpose warm-season plant that offers both leaf and grain sources of human food, animal fodder and ornamental products (University of Kentucky 2011). Amaranth is one of only a few plants whose leaves can be eaten as a vegetable and its seeds as a grain. Table 1 contrasts the nutritional content of amaranth seeds and leaves with that of maize, demonstrating the nutritional superiority of amaranth. The health and nutritional benefits of both grain and leaf amaranth could potentially address issues of growing food insecurity and nutritional gaps in sub-Saharan Africa

(Mukhebi *et al*. 2011) that pose a substantial challenge to human welfare and economic development in the region (Todd 2004).

Table 1: Nutritional composition of amaranth and maize

Produce	Nutrients			
	Iron	**Zinc**	**Proteins**	**Ash**
Leaf amaranth	12.4 mg	4.1 mg	4 mg	2 mg
Grain amaranth	7.6 mg	3 mg	15 g	160 mg
Maize	0.5 mg	0.5 mg	3 g	2 mg

Source: Unpublished project report of Africa Food Security Initiative Phase 2 – Spatial Targeting Tools Project

The ability and high potential of amaranth to grow in adverse environmental conditions and reach maturity in a short period of time compared to other crops could potentially reduce the variability of food production cycles in dry rural areas, where nutrition is needed most (Kyagulanyi *et al*. 2016). This is particularly important because adverse climatic conditions (low rainfall, heat waves, severe drought) are among the main reasons for food deficits in Africa (Mukhebi *et al*. 2011), and are expected to get worse due to ongoing climate change (Sasson 2012). Amaranth's adaptability to adverse environmental conditions and rich nutrition content could make it a useful crop for coping with the risks of food insecurity and in advancing nutrition and food security conditions in dry regions.

Amaranth has appeared intermittently in the literature since its effective rediscovery in the early 1970s. An ad hoc report by the US National Academy of Science (1975) sheds light on 36 underexploited tropical plant species, including amaranth, that could broaden the food base and provide supplementary sources of nutrition for humans, as well as have potential economic value. Since that seminal work, researchers have been keen to discover more about both grain and leaf amaranth in respect of plant structure, morphology, genetic varieties, nutrition characteristics (protein, amino acid, lysine), diseases and pests, agronomy, taxonomy, growth and development (National Research Council 1984; Bressani 1989; Kauffman & Weber 1990; Stallknecht & Schulz-Schaeffer 1993; Myers 1996; Achigan-Dako *et al*. 2014; Muriuki 2015; Njoki 2015). Further literature has focused on amaranth's drought resistance (Liu & Stützel 2004), tolerance to soil salinity (Omamt *et al*. 2006), and various health benefits of amaranth in the human diet (Krulj *et al*. 2016). More recent studies have focused on topics such as its antioxidant content, potential product applications (e.g. mixed flour composition), and processing (e.g. technologies to extract oil from amaranth seed, manufacture of protein concentrates) (Venskutonis & Kraujalis 2013; Muyonga *et al*. 2014; Njoki 2015; Krulj *et al*. 2016; Rybicka *et al*. 2019).

In East Africa, the amaranth value chain is relatively underdeveloped in terms of production areas and marketed volume (Nzomo *et al*. 2014). A proportion of amaranth leaf is lost in each of the pre- and post-harvest phases of the production system. Furthermore, producers consume a proportion of amaranth leaf at home, and amaranth frequently serves as a gift within social and family groups (see Table 2). The remaining amaranth leaf is mostly sold at the farm gate to individual consumers, to traders and collectors, and to wholesalers/retailers, with limited value-adding activities (Africa Food Security Initiative 2013). Table 2 summarises the percentage of amaranth that goes to each trading channel (commercial and non-commercial).

Table 2: Fractional share (per year) of trading channels of amaranth leaf value chain

Value chain channels (amaranth leaf)	Share
Fraction sold to market	66.9%
Fraction consumed by producers	13.5%
Fraction post-harvest loss	0.3%
Percentage given as gifts and other non-commercial uses	19.3%

Source: AVRDC and JKUAT baseline database (see footnote 4 for number of observations)

3. Materials and methods

We employed a quantitative model that relates amaranth leaf product markets to production and new technology uptake. We specified exogenous scenarios representing a departure from a business-as-usual baseline to which existing data was applied for model calibration. Endogenous variables (e.g. area planted to amaranth, amaranth price, and profit) were tracked over time, and also represented as departures from baseline values. Profitability was measured as the sum of the producers' profit over time.

Our approach offers an important advantage over conventional value chain analysis (e.g. Kaplinsky & Morris 2001) that focuses primarily on mapping a given value chain at a point in time, rather than specifying the mechanisms by which value chains evolve over time in response to shocks or interventions. We use a value chain approach, augmented by the specification of dynamic relationships amongst variables so as to more completely represent the timing and interconnected complexity of change in the chain (Baker *et al*. 2017). We used the system dynamics (SD) modelling and analytical paradigm developed at the Massachusetts Institute of Technology in the mid-1950s.[1] SD is an approach to solving problems based on dynamic behaviour in complex systems. It specifies systems of non-linear differential equations to model the consequences of system behaviour given interactions and feedbacks between different actors and/or decisions over time.

We visualised and modelled the amaranth value chain studied in this paper through the use of stock and flow diagrams. Accumulations of products held by each value chain actor at a point in time are denoted as stocks. Trade between value chain actors via various trading channels are represented as flows, and the production level conversion of raw materials to products is represented as co-flows. These stocks and flows are presented in figure 1[2] for the leaf amaranth value chain, along with the mediating technical parameters.

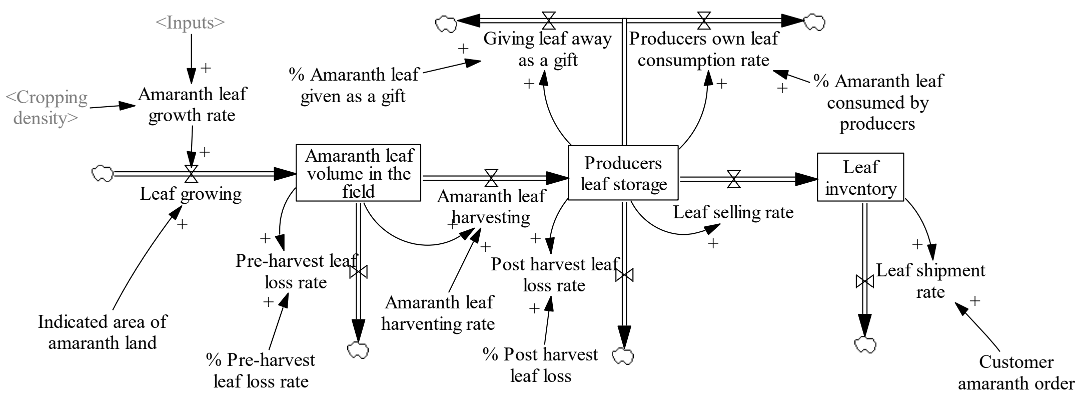

Figure 1: Amaranth leaf value chain

We established a market equilibrium by balancing inventory that producers or processors have at hand (i.e. "leaf inventory" in Figure 2 as available product) with their "reference (or desired) inventory coverage" (Sterman 2000). The interaction between inventory and desired inventory determines price. Price changes affects producer investment decisions in both the short and long term.

[1] http://www.systemdynamics.org/DL-IntroSysDyn/origin.htm

[2] In essence, at the background of stocks and flows, a set of integral (**$Stock_t$ = INTEGRAL(Inflow-outflow) + $Stock_{t-1}$**) and differential equations (**d(stock)/dt = Net Change in Stock = Inflow(t) - Outflow(t)**) operate the model (Sterman 2000). A full list of model equations is available from the authors upon request.

Producer and consumer responses to changes in price are modelled on the basis of an assumed price elasticity of demand and elasticity (or sensitivity) of price to inventory coverage. We assume that consumers react quickly to changes in price through adjusting demand (we assume a price elasticity of demand of -0.75 – see Levin & Vimefall (2015) for similar elasticity value for agri-food and maize in Tanzania and Kenya). However, producer response to changes in price (and hence profitability) is smoothed (to form future expectations of prices) based on perceived changes in price and the amount of time required to react to such changes (i.e. time it takes to decide whether to increase or decrease or leave unchanged the area allocated to amaranth production).

Table 3 summarises elasticities and consumer and producer response time to changes in the market. A full list of equations of our model is available upon request from the corresponding author.

Table 3: Elasticities and adjustment times used in the model

Item	Value	Unit	Note
Initial land allocated to amaranth	0.5	Hectare	
Leaf price elasticity of demand	-0.75	Unitless	Levin & Vimefall (2015)
Amaranth area elasticity	0.2	Unitless	McKay *at al*. (1999); Levin & Vimefall (2015)
Alternative crop area elasticity	0.2	Unitless	McKay *at al*. (1999); Levin & Vimefall (2015)
Reference (desired) inventory coverage	10	Week	10 weeks of customer demand
Demand adjustment delay	2	Week	Time it takes consumers to respond to changes in price
Time to adjust short run price expectations	26	Week	Price smoothed over 26 weeks to smooth spot-price variation
Time to adjust land allocation to various crops	52	Week	Time it takes to switch land use from one crop to another after decision is made

The model was populated with data on the amaranth leaf value chain for Tanzania obtained from the World Vegetable Center (AVRDC) and the Jomo Kenyatta University of Agriculture and Technology (JKUAT). The dataset includes 44 farm-level observations.[3] Due to a lack of time-series data, we used cross-sectional data to initialise the model at the beginning of 2016. The database includes variables such as inputs (manure, inorganic fertiliser, pesticides, irrigation, labour, nursery (e.g. seed) and other inputs), yield (produced volume of amaranth per hectare), and trading channels. We validated both model structure and data with the JKUAT team in Nairobi in June 2015 to finalise the initial model parameterisation. Other structural drivers (relationships among model components) that might influence model results and the conceptualisation of interventions were discussed and finalised with the team, as were the range of interventions to be examined as scenarios. We conducted several SD model-validation tests, such as structure assessment, dimension consistency, structure-behaviour and extreme condition tests, as suggested in Sterman (2000). Model outcomes were reasonable under all validation tests; more calibration and validation details are available from the authors upon request.

[3] Originally the database included 49 observations. Five observations were omitted due to their unrealistic (500 tons yield per hectare per year) yield volume.

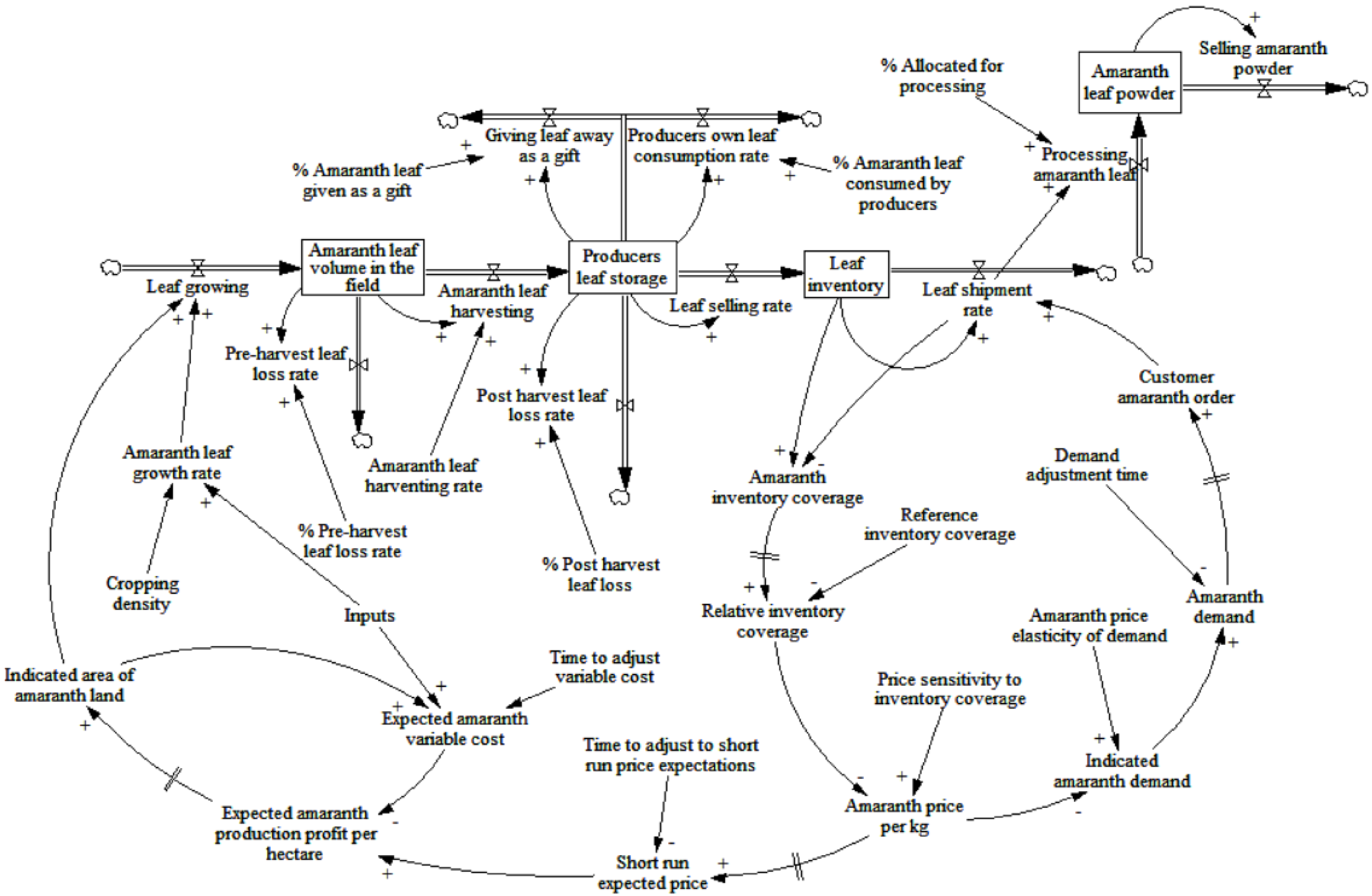

Figure 2: Amaranth grain value chain, leaf value chain, and price setting and investment decision

Intervention scenarios

In this section, we provide a description of baseline and intervention scenarios to evaluate producer responses to different changes in the amaranth value chain, with a primary focus on standard measures of return (net present value, or NPV) at the farm level.

Scenario 1 (baseline): In this scenario, we ran the model based on amaranth production and marketing data collected in Tanzania (see previous section). The purpose of our baseline scenario is twofold. First, it provides a form of validation of how well our model replicates the given data and structural relationships. Second, it provides a benchmark to compare the alternative scenarios (2 to 4). Tables 4 and 5 summarise the baseline data for the inputs used (and input costs) per hectare (ha) and the production and demand parameters respectively.

Table 4: Inputs used and costs in amaranth production

Input	**Quantity**	**Unit**
Manure	4 500	kg/ha
Inorganic fertiliser	546	kg/ha
Pesticide	394	kg/ha
Input cost	**Value**	**Unit**
Manure cost	474	USD/ha
Inorganic fertiliser cost	424	USD/ha
Pesticide cost	916	USD/ha
Labour cost	92	USD/ha
Nursery cost	2 023	USD/ha
Harvesting cost	118	USD/ha
Marketing cost	82	USD/ha
Other costs	45	USD/ha

Source: AVRDC and JKUAT baseline database

Table 5: Production and market parameters

Initial production and demand	**Value**	**Unit**
Leaf amaranth production (sum of two seasons per year)	14 400	kg/year/ha
Initial leaf amaranth demand	9 625	kg/year/ha

Source: Estimated based on AVRDC and JKUAT baseline database

Scenario 2 (better seed varieties): In this scenario, we included the use of seed from improved varieties. The productivity increase achieved is based on baseline data provided by the AVRDC. This scenario includes changes in productivity of annual leaf amaranth from 28 800 to 34 000 kg per ha. The remaining values for variables listed in Tables 4 and 5 remain unchanged.[4]

Scenario 3 (better seed varieties and a permanent increase in demand): In this scenario, we combined the use of improved seed varieties with an increase in demand by way of marketing interventions. This scenario is motivated by the debate about low consumer consumption of amaranth. We investigated whether a permanent increase in amaranth demand benefits producers, taking into account the costs associated with marketing interventions to increase demand (marketing intervention targets motivating use of amaranth products to absorb extra supplies that come with adopting better amaranth seed varieties – see top right-hand corner of Figure 2[5]). These interventions could include promotion or consumer education activities that raise awareness of, and demand for, amaranth. We simulated this by modelling a permanent, gradual increase in demand of 15% (shifting demand intercept) from the end of year 2016 (week 52) over a four-year time horizon (i.e. the 15% increase

[4] Data suggests no cost differences among different varieties of amaranth seed.

[5] We only provide a conceptual model to represent amaranth leaf processing to powder to motivate the marketing strategy for amaranth products. However, further research is needed to evaluate the economic viability of such business models and consumers' willingness to pay for such products.

in demand will be fully realised after four years of logistic distribution). The logistic distribution imposes an S-shaped adoption profile, featuring a 15% increase in demand over a four-year time horizon to avoid a sudden shock to the model and to recognise that marketing interventions do not change demand instantly. We assume for simplicity that this intervention will increase direct marketing costs proportionally (i.e. a 15% increase in demand leads to a 15% increase in marketing costs), although more research is required to quantify and characterise this cost factor and its likely effect on the relationships represented in the SD model.

Scenario 4 (increase of profitability of alternative crops such as maize): This scenario was motivated by the fact that decisions on land allocation amongst crops are made on the basis of expected profitability and the opportunity cost of producing other crops (such as maize). In this scenario, we exogenously manipulated the profitability of alternative crops by 20% from the beginning of the simulation to evaluate how changes in the profitability of competing crops affect land allocation and the profitability and financial attractiveness of amaranth production. The 20% increase in alternative crop profitability will be fully realised after four years, again using a logistic distribution over time.

4. Model settings and results

The model was run over a ten-year (520 weeks) time horizon (from the end of 2015 to the end of 2025). Our policy interventions of marketing (scenario 3) and changes in alternative crop profitability (scenario 4) were introduced at the end of year 2016 (week 52). Scenario 2 was introduced at the beginning of the simulation to highlight the effects of changes in supply on prices. In Figure 3 and Figure 4 below, runs 1, 2, 3 and 4 represent scenarios 1 (baseline), 2 (better seed variety), 3 (better seed variety and increase in demand), and 4 (exogenous increase in alternative crop profitability) respectively. In Table 6 and Table 7, we summarise cumulative profits to evaluate the short- and long-term changes in profitability.

We arbitrarily fixed farmland area to one hectare. We assumed an initial land area allocated to amaranth production of 0.5 hectare (with the other 0.5 hectare allocated to alternative crops). The amount of land allocated to amaranth varies over time based on the factors outlined above (i.e. expected profitability and the opportunity cost of producing other crops such as maize). To take into account the profitability of alternative crops, we introduced an exogenous parameter named "normalised alternative land use profitability" to the model. When the value of "normalised alternative land use profitability" is 1, less than 1, and greater than 1, it means profitability of alternative crops is equal to, less than, and more profitable than amaranth respectively. We assumed an area elasticity of land allocation of 0.2 – see McKay *at al*. (1999) and Levin and Vimefall (2015) for similar approaches.

Amaranth production occurs twice per year as two crop cycles. Leaf amaranth is harvested all at once. Season 1 starts in February and ends in May of each year. Season 2 starts in June and ends in September of each year. Such seasonal production patterns introduce seasonal effects in the supply and price of and demand for amaranth. Figure 3 shows the pattern of amaranth leaf prices over time for each scenario. Prices reach their minimum during peak harvest time and increase thereafter, and the cycle repeats itself each season.

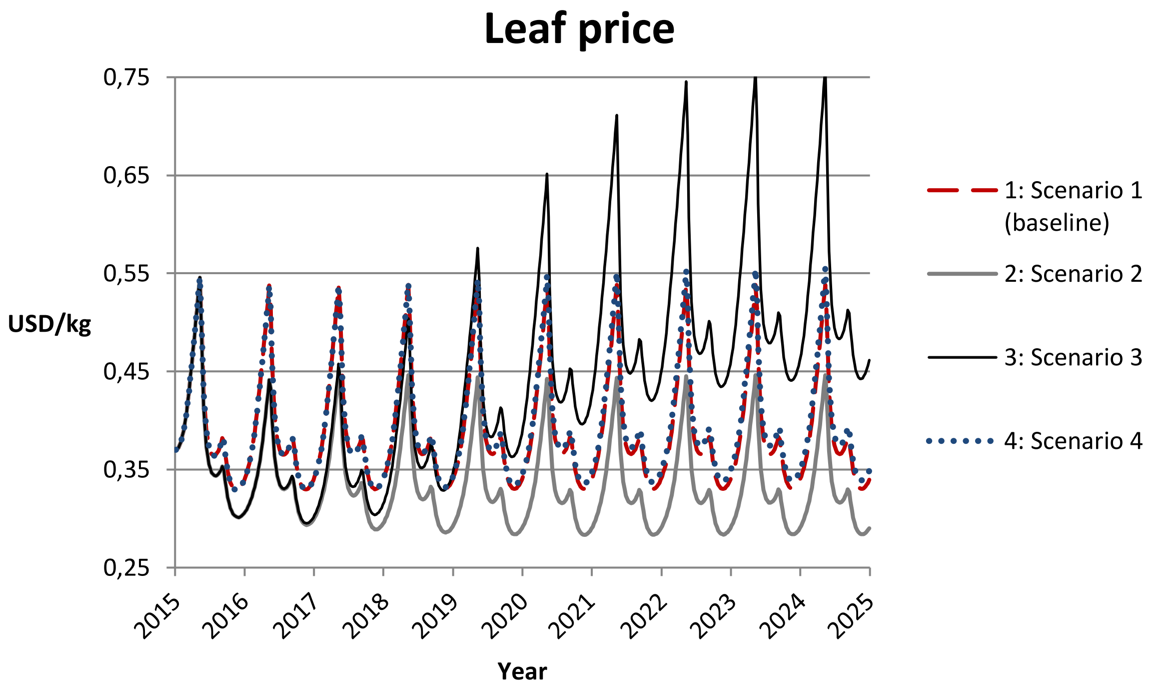

Figure 3: Amaranth leaf price per kg over time (scenario 1: baseline; scenario 2: improved seed varieties; scenario 3: improved seed varieties and a permanent increase in demand; scenario 4: an exogenous increase in alternative crop profitability)

Scenario 1 (dashed red trend) shows the amaranth leaf price behaviour under baseline assumptions. The baseline amaranth leaf price exhibits stable, oscillatory behaviour because of the seasonal nature of amaranth production. The price of amaranth leaf in scenario 2 (improved varieties) oscillates at a dampened level compared to the baseline scenario due to the 18% increase in amaranth leaf production. This causes an increase in the supply of amaranth leaf, at a lower price. Scenario 3 (improved seed varieties and a permanent increase in demand) combines with scenario 2 and provides a permanent 15% increase in demand from the beginning of 2017. Given the gradual increase in demand from the beginning of 2017, the amaranth leaf price begins to increase from mid-2018, with the late response in price due to delays in the marketing intervention effect on consumer demand. Prices peak and stabilise from 2022 onwards due to reduced consumer demand and a greater supply from producers in response to higher prices.

Amaranth leaf prices in scenario 4 (increase in profitability of alternative crops) grow slightly from mid-2020 and onwards because we assume that the profitability of alternative (or substitute) crops increases gradually by 20%. This subsequently leads to less land being allocated to amaranth production, lowering amaranth supply and increasing prices. However, higher prices increase profit margins for amaranth, which in turn stabilise prices, albeit at a slightly higher level relative to the baseline scenario.

Table 6 shows the cumulative profit of amaranth leaf production per year for each scenario, and Table 7 summarises the percentage change in cumulative profit of amaranth leaf production over the simulation time horizon. The annual cumulative profit of scenario 1 (baseline) is relatively stable and ranges from a minimum of US$2 904 to a maximum of US$2 909, with a mean of US$2 907.

The cumulative profit (expressed per hectare to enable comparison among scenarios) of amaranth leaf production in scenario 2 exhibits somewhat different behaviour than does the baseline (scenario 1). Scenario 2 assumes higher amaranth leaf production (greater supply) as a result of using a more productive variety of amaranth seed. Even though increasing amaranth leaf supply leads to a lower amaranth price, the cumulative profit of amaranth increases only slightly, at just 0.7% higher than scenario 1. On the other hand, the cumulative profit in scenario 3 greatly exceeds both scenarios 1 and 2, with an increase in profit of 76% compared to scenario 1, because it assumes a permanent 15% increase in demand, in addition to using more productive amaranth seed varieties (despite higher marketing costs). Thus, increasing production alongside measures that raise demand leads to higher profitability. Cumulative profits in scenario 4 increase at a diminishing rate from 2019 onwards. This is because the lower supply of amaranth as a result of declining land allocation to amaranth production increases the price, and hence the profit margin of amaranth production. The increase in profit margins more than offsets revenue losses that arise as a result of a lower supply of amaranth.

Table 6: Amaranth leaf value chain cumulative profit per year

	Amaranth leaf value chain cumulative profit (USD/ha)			
Year	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
2016	2 904	2 904	2 904	2 904
2017	2 905	2 982	2 968	2 906
2018	2 905	3 039	3 141	2 918
2019	2 906	2 964	3 610	2 952
2020	2 908	2 905	4 486	2 999
2021	2 909	2 885	5 508	3 043
2022	2 909	2 891	6 398	3 075
2023	2 908	2 899	7 016	3 097
2024	2 908	2 902	7 373	3 109
2025	2 908	2 902	7 768	3 116
Cumulative	29 070	29 273	51 172	30 119

Source: Model results. The table is adjusted to represent each scenario on a per hectare basis.

Table 7: Amaranth leaf value chain percentage change in cumulative profit (end of simulation)

Items	**Summary of gains and losses**
Scenario 2 vs. 1	0.7%
Scenario 3 vs. 1	76%
Scenario 4 vs. 1	4%

Source: Model results

Figure 4 shows how land area over time changes in each scenario. As expected, scenario 3, with the highest cumulative profit per hectare, utilises the most land for amaranth production (i.e. as profits from amaranth production go up, farmers allocate more land for amaranth production). By the end of the simulation, about 24% more land is allocated to amaranth in scenario 3 relative to scenario 1. Land allocation to amaranth production in both scenarios 1 and 2 remains almost the same. However, scenario 4 uses less land for amaranth relative to the other scenarios. Notably, by the end of the simulation, scenario 4 uses 2% less land but is 4% more profitable than the baseline scenario.

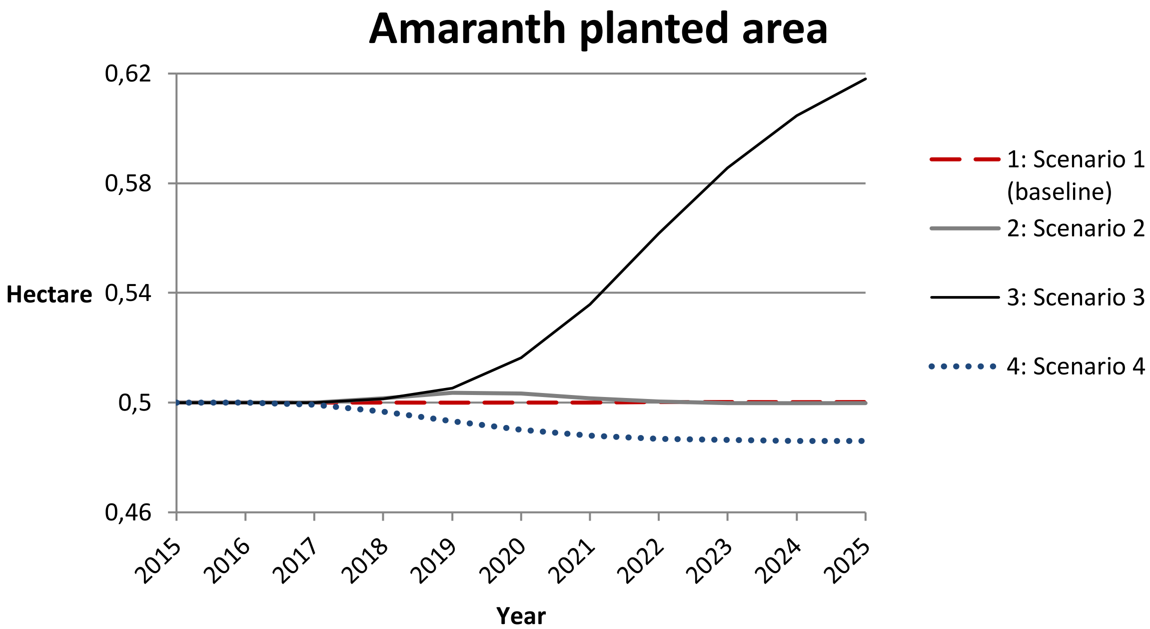

Figure 4: Amaranth leaf planted area in hectares (scenario 1: baseline; scenario 2: improved seed varieties; scenario 3: improved seed varieties and a permanent increase in demand; scenario 4: an exogenous increase in alternative crop profitability)

5. Discussion and conclusion

This paper has examined a number of development scenarios for the uptake of amaranth by smallholder farmers. To the authors' knowledge, this is the first study that integrates production and economic analysis of amaranth over multiple time periods and including dynamic feedback and adjustments, and the first that includes multiple stages of amaranth production and marketing value chains based on endogenous pricing and investment. The paper extends the existing SD modelling framework to smallholder value chains, particularly by offering advances on conventional microeconomic analysis of changes such as farm-level decision making, and evaluating the feedback effect of multiple policy interventions at the production and market level in the value chain. Our modelling approach, as has previous studies on the SD modelling approach applied to livestock and aquaculture systems (see Hamza *et al*. 2014; Dizyee *et al*. 2017; Ouma *et al*. 2018; Dizyee *et al*. 2019), extends the utility of SD to crop modelling to show the versatility of the SD modelling approach in modelling dynamic agricultural systems in general.

The health and nutritional benefits of the expanded consumption of both grain and leaf amaranth could potentially contribute to food security and nutritional improvement in sub-Saharan Africa. Amaranth's suitability for production in adverse and increasingly variable environmental conditions could potentially reduce the variability in its availability in food production cycles of some of the most vulnerable regions relative to other, less-resilient crops such as maize. Widespread adoption of amaranth and an associated development of market mechanisms, however, is dependent on appropriate incentives. Our review of the amaranth literature (section 2 and Table 1) and results (see Table 6 and Table 7) indeed reveal that amaranth has substantial potential to supplement nutrition and contribute to producer incomes. However, interventions that target only amaranth production (using better seed varieties) at the producer level have small effects on producers' profit (a cumulative change of between 0.5% and 1.1% over ten years). In contrast, combining these interventions with those at the market level (increased demand for amaranth products) substantially increased the profitability of amaranth production and consequently increased amaranth's planted area. Our results are consistent with the existing literature that documents the nutrition and health benefits (Schröter *et al*. 2018; Rybicka *et al*. 2019) and income-generating opportunities for smallholder producers of indigenous vegetables such as amaranth (Chagomoka *et al*. 2014; Ebert 2014).

Although adopting better seed varieties did increase amaranth production (which potentially improves food security and the nutritional condition of consumers) and, to a lesser extent, profit, such minor changes in profit are unlikely to promote substantial adoption of amaranth production. Indeed, the land allocated to amaranth did not change under the improved seed variety scenarios because higher amaranth production was offset by a lower amaranth price. In contrast, changes in demand for amaranth resulted in a substantial, sustainable increase in land allocation for amaranth production as producers gained more income from producing amaranth. This quantitative conclusion supports previous conceptual work that advocates a supply chain orientation of primary industry policy (Baker *et al*. 2017). It also contributes a quantitative example to the emerging field of chain failure, wherein conventional internalisation of market failure is refined to refer to actors that lie within, or beyond, the value chain in question (Griffith *et al*. 2015).

Comprehensive cost-benefit analysis targeting all actors in the value chain is deferred to further research. The available data did not include cost and profitability beyond the farm gate, and importantly excluded amaranth-processing technologies and value-added products. The extension of the current model to deeper analysis of these sectors and stakeholders, particularly its endogenous price and investment elements, is an exciting proposition that will have implications for a number of food and agricultural initiatives in sub-Saharan Africa. An important element of such an extension is substitution between crops, which the current model addresses in an aggregate manner due to a lack of data. Further research should also aim at highlighting critical bottlenecks that limit amaranth's utilisation. These include a lack of quality and scale of inputs (e.g. seed) to produce amaranth. Similarly, amaranth planting and harvesting are mostly done on small plots of land that rely on manual labour. Investments that target enhanced amaranth planting, harvesting and food-processing (e.g. bakery, powder) technologies could be key to unlocking the potential of amaranth.

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