Understanding Cassava Dynamics in Different Development Contexts

A case study in the series:
Economic foresight for understanding the role of investments in agriculture for the global food system

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1 Introduction and Context

Cassava (*Manihot esculenta*) is a tuber grown throughout the tropics. Cassava is a multifunctional crop with many uses ranging from human consumption to animal feed, to feedstock for industrial processes (Falade & Akingbala, 2011). The crop is often considered resilient under conditions of climate change, but may also be adversely affected by pests and disease dynamics (Jarvis, Ramirez-Villegas, Campo, & Navarro-Racines, 2012).

Use and consumption of cassava varies regionally. Often considered a crop for "drought, war and famine," (Burns, Gleadow, Cliff, Zacarias, & Cavagnaro, 2010), cassava starch is also an important feedstock for many industrial food products and processes (Breuninger, Piyachomkwan, & Sriroth, 2009). Cassava in root form is a perishable commodity, but is readily traded as chips and as starch, competing favorably with maize, wheat, rice and potato starches (Waterschoot, Gomand, Fierens, & Delcour, 2015).

Given this dichotomy of a crop for the poor versus an important feedstock for multiple industrial processes, several questions arise regarding the role of the crop as an entry point to development interventions. The joint activities for the PIM Global Futures and Strategic Foresight project and the Roots, Tubers and Bananas Earmark 5.1 initiative presented here are intended to help disentangle some of the complexities of this important crop.

We present our review of cassava dynamics in three sections. First, we illustrate global cassava trends using the IMPACT Model (Robinson et al., 2015) and address some of key findings and challenges associated with the global model of the agricultural sector. Second, we examine the evolution of the cassava trading network over time and the importance of the crop in the carbohydrate market, focusing principally on SE Asia and including North America as a competing producer of related commodities. Finally, given the role of investment in new crop technologies as one potential lever in driving development outcomes, we develop a case study to better understand the relationships between a new cassava technology (i.e., cassava with small granule starch) and the assumptions required to assure adequate return on investment.

2 Evaluating Cassava Trends Using the IMPACT Model

The IMPACT Model, developed by the International Food Policy Research Institute, is a partial equilibrium model of the agriculture sector. IMPACT enables modeling of production and global trade of over fifty different agricultural commodities, accounting for producer and consumer prices, endogenous and exogenous yield shocks (positive and negative), and the general impacts of climate change more broadly (Robinson et al., 2015).

The IMPACT model includes estimates of crop yields under conditions of climate change. The yield impact of climate change is modeled using mechanistic crop models for a small subset of the crops. For the rest of the crops included in IMPACT, the expected yields under different climates are derived from the modeled crops and other foundational information.

Climate change is the most serious, chronic challenge that all countries around the world are facing, especially in the developing regions where agriculture is one of primary economic activities. Agriculture is vulnerable to changes in climate variables such as precipitation and temperature, generating adverse production conditions such as drought, floods, pest, and diseases, among others.

For this reason, it is crucial to understand the potential effects of climate change on agriculture systems. Integrated approaches are required that draw from the best available information to support the decision-making process. These integrative approaches consider biophysical impacts on climate change across a variety of agricultural systems, include consideration of trade, and facilitate the evaluation of issues around global food and nutritional security.

To understand the impact of climate change on foreign agricultural trade, IMPACT simulates a climate change scenario from the present to 2050. The climate change scenario (labeled CC in the following text) is an average of IMPACT model runs, each run incorporating a distinct global climate model.[1] An IMPACT "no climate change" scenario (referred to as No-CC) holds climate constant at its current levels, to establish a baseline point of comparison. Both the CC and No-CC scenarios were modeled under the assumption of high population and GDP growth combined with moderate-to-high greenhouse gas emissions.[2]

The IMPACT model facilitates exploration of regional variation in agriculture system response to different plausible future socioeconomic and climatic scenarios in order to better understand how we might prepare to mitigate future challenges. The scenarios regarding socioeconomic and radiative forcing are described in Table 1.

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[1] Five different General Circulation Models were used to project the impact of future climate on trade.

[2] Four representative concentration pathways (RCPs) were selected and defined by their total radiative forcing (cumulative measure of human emissions of GHGs from all sources expressed in Watts per square meter) pathway and level by 2100. The RCPs were chosen to represent a broad range of climate outcomes, based on a literature review, and are neither forecasts nor policy recommendations (IPCC, 2015).

Table 1: Description of select Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathway (RCPs)

Shared Socioeconomic Pathways (SSPs)	Description	Representative Concentration Pathway (RCP)	Scenarios (CC)
SSP 2	Business as usual, total population, GDP and international trade to continue on their current trajectory	**RCP 4.5:** Stabilization of emissions to avoid overshooting 4.5 W/m2 by 2100	Moderate: SSP2_RCP4.5 SSP2_RCP8.5 (Business as usual)
SSP 3	Highly fractured, countries pushing apart, high problems with mitigation, high problems with adaptation	**RCP 8.5:** Rising radiative forcing pathway leading to 8.5 W/m2 in 2100.	Pessimistic: SSP3_RCP4.5 SSP3_RCP8.5 (Fragmentation)

The key analyses were performed at two geographic scales, regional and national based on the overall global analysis. The regional results are weighted aggregations of all nations within the defined regions. For the national results, we focus on the major cassava producers reported in IMPACT (see Table 2).

Table 2: Regions and Countries

Sub region	Latin-American (LAC), Eastern Asia Pacific & Oceania (EAP), Southern, Northern and Western Europe (EUR), Eastern European (FSU), Western Asia and Northern Africa (MEN), Northern America (NAM), Southern Asia (SAS), Middle, Eastern, Southern and Western Africa(SSA) and finally World.
Countries	Major cassava producers: Thailand, Indonesia, Philippines, Viet Nam, Nigeria, Brazil, Cambodia, Angola, India, Cameroon, Mozambique, Paraguay, Colombia, and Brazil.

In order to structure the analysis to understand the global trends in cassava, we present the results in terms of supply side dynamics, demand side perspectives, and some general conclusions at the global scale.

2.1 Supply

Generally speaking, the future global supply of cassava trends downward in the moderate as well as pessimist scenarios (Table 3). The results show a pronounced decline in production in the LAC region across all scenarios, while the EAP region will gain a small increase in production under the scenarios with higher radiative forcing. Country level results presented in Appendix A indicate that, within the LAC region, Brazil, Paraguay, and Costa Rica will have negative trends on cassava production, while Colombia may see positive change. In Asia, the Philippines, Cambodia, and Thailand are projected to see increased productivity. However, nations such as Viet Nam show the opposite behavior. Africa exhibits high vulnerability to climate change stress on cassava production. This trend is particularly evident in Angola, Cameroon, and Nigeria. In contrast, the projections for Kenya would seem to indicate an increase in cassava production potential (Appendix A).

Table 3: Percentage differences for change in production by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP2	RCP8.5_SSP3
EAP	-0.36	-0.32	0.88	0.24
LAC	-6.08	-6.04	-8.09	-9.40
SAS	-3.34	-3.25	-4.93	-5.54
SSA	-2.07	-2.02	-2.21	-3.32
WLD	-2.46	-2.42	-2.69	-3.76

Though production may increase in many areas due to economic drivers, the aggregated global results suggest that yields will tend to decrease across all regions (Table 4). This considers both the yield shock associated with climate change as well as countervailing forces such intrinsic and economically driven productivity growth. There are regional differences, however, with the EAP region showing only moderate declines in yields (and, in fact, modest yield growth under one scenario).

Yields are projected to decrease in Asia under most scenarios with some differences at the national level. Philippines shows potential increases, while Thailand, Vietnam, and Cambodia would have a negative effect derived from climate and socioeconomic shocks. Importantly, these trends do not consider other technological advances and new varieties, suggesting that additional study is needed to understand the impact of new varieties from the macro perspective.

Latin America and the Caribbean show significant impacts on yield, with substantial negative impacts projected for Paraguay, Brazil, and Costa Rica. Colombia is a potential outlier as one of the only countries in this region with projected yield increases. In Africa, results for yield more or less mirror results for production, again with Kenya as the possible exception to generally negative trends.

Table 4: Percentage differences for change in yield by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP2	RCP8.5_SSP3
EAP	-0.86	-0.85	0.37	-0.42
LAC	-5.66	-5.66	-7.13	-8.56
SAS	-4.08	-4.07	-5.13	-6.02
SSA	-2.47	-2.46	-2.24	-3.57
WLD	-2.76	-2.75	-2.64	-3.91

2.2 Demand

In the IMPACT model, the total demand for cassava is composed of feed, household, intermediate and “other” demand. This is derived as a function of socio-economic drivers (total, urban and rural population, GDP growth, etc.) at different levels corresponding to the narratives for each scenario modeled (business-as-usual and fragmentation).

The results show a general decline in cassava demand under climate change compared to the baseline No-CC scenario. The IMPACT model does project increased demand for cassava in North America, especially in the fragmentation scenarios (see Table 5); this is likely attributable to increased demand for cassava as livestock feed or other intermediate processes. On the other hand, the EUR and LAC regions are projected to see relatively significant decreases in demand under the fragmentation scenario.

Table 5: Percentage differences for change in Demand by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP2	RCP8.5_SSP3
EAP	-2.138	-2.087	-2.339	-3.135
EUR	-4.567	-4.604	-5.708	-8.274
FSU	-0.397	-0.412	-0.238	-0.368
LAC	-3.752	-3.414	-5.372	-6.883
NAM	-0.037	-0.139	3.474	5.510
SAS	-1.281	-1.308	-1.264	-1.883
SSA	-2.361	-2.384	-2.372	-3.466
WLD	-2.463	-2.427	-2.699	-3.770

2.2.1 Types of use

Demand for cassava production varies substantially be region. Cassava demand is spread across unprocessed root for human consumption, cassava chips, cassava starch, and other derivative and value added products, including biofuels. As mentioned, the perishable nature of cassava root results in a commodity that tends to a locally traded and consumed. In the following sections, we summarize expected changes in household demand, demand for cassava as livestock feed, biofuel feedstock, and other uses (e.g., ethanol for human consumption, sweeteners, etc.).

Relative household demand for cassava is projected to decline universally across all scenarios. This suggests that, at the household level, other foods are substituting for calories once derived from cassava and related products.

Table 6: Percentage differences for change in Household demand by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP2	RCP8.5_SSP3
EAP	-1.234	-1.261	-1.220	-1.813
EAS	-1.235	-1.262	-1.221	-1.814
EUR	-0.562	-0.577	-0.521	-0.778
FSU	-0.358	-0.369	-0.311	-0.470
LAC	-0.736	-0.752	-0.708	-1.065
MEN	-1.313	-1.341	-1.305	-1.931
NAM	-0.663	-0.681	-0.616	-0.938
SAS	-1.264	-1.293	-1.240	-1.855
SSA	-2.060	-2.105	-2.070	-3.092
WLD	-1.842	-1.880	-1.845	-2.753

Changes in livestock related demand are more heterogeneous than those associated with household demand. In all scenarios, demand is appears to be increasing in North America. An interesting finding is that under the higher radiative forcing scenarios, cassava demand for livestock is substantially higher in both North America and the former Soviet Union. This higher demand in the temperate regions may be offsetting production shocks for other commodities such as wheat and/or maize.

Table 7: Percentage differences for change in livestock demand by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP2	RCP8.5_SSP3
EAP	-4.501	-4.542	-5.215	-7.009
EUR	-4.815	-4.846	-6.034	-8.729
FSU	-1.402	-1.803	7.725	15.513
LAC	-6.010	-6.016	-8.870	-12.578
MEN	-4.052	-4.199	-2.330	-1.733
NAM	0.400	0.208	6.044	9.160
SAS	-2.074	-2.125	-2.444	-3.308
SSA	-2.940	-3.023	-2.949	-4.292
WLD	-3.851	-3.904	-4.579	-6.480

Though biofuel feedstock demand will generally follow the broader cassava trends, actual demand for cassava as a biofuel feedstock is heavily dependent on both policy (e.g., ethanol fuel policy) and trending prices driving demand for competing crops, especially maize. As illustrated in Table 8, there is some variation in demand for cassava for biofuels, but the change in demand due to climate change pressure is relatively uniform across regions and scenarios.

Table 8: Percentage differences for change in Biofuel Feedstock by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP3	RCP8.5_SSP4
EAP	-0.690	-0.703	-1.065	-1.040
LAC	-0.513	-0.523	-0.788	-0.771
MEN	-0.947	-0.965	-1.460	-1.427
SSA	-1.374	-1.399	-2.123	-2.072
WLD	-0.701	-0.714	-1.081	-1.056

Other demand (e.g., cassava for ethanol for human consumption, sweeteners, etc.) is generally projected to decline across all regions under conditions of climate change (Table 9). This is likely due to more favorable processes for substitute commodities and speaks to the importance of reducing unit costs of production and, likewise, increasing yield of cassava starch, one of the key drivers of demand for cassava as an input into other products.

Table 9: Percentage differences for change in other demand by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP2	RCP8.5_SSP3
EAP	-1.320	-1.351	-1.310	-1.953
EAS	-1.354	-1.381	-1.348	-1.999
EUR	-0.918	-0.882	-0.916	-1.277
FSU	-0.387	-0.400	-0.311	-0.505
LAC	-0.744	-0.764	-0.690	-1.062

MEN	-1.340	-1.375	-1.338	-2.001
NAM	-0.770	-0.791	-0.716	-1.093
SAS	-1.311	-1.342	-1.289	-1.958
SSA	-2.368	-2.420	-2.391	-3.576
WLD	-1.843	-1.880	-1.846	-2.756

2.3 Conclusions

Though international trade in cassava or any other agriculture commodity is influenced by production prices, complex competition among substitute products, tariff and non-tariff barriers, and other factors such as transport fuel costs, the IMPACT model does offer valuable insights on global cassava trends. The trends associated with increasing demand in North America, the increased importance of cassava production in East Asia and Pacific, and the expected declines in cassava production in Latin America (once a key producer region) underscore the dependence of cassava demand on both the policy landscape and the pressures on other competing commodities.

Overall, the global supply of cassava appears to be on the decline. This is largely due to the combination of competition from other crops with greater economic efficiency and uneven distribution of climate impacts on the production system.

The versatility of cassava is one of the key attributes that suggests that even in a competitive environment, that there is potential for cassava as a development intervention. The role of starch production and the potential to use cassava chips as inputs to several industrial uses might facilitate new interventions, promoting cassava consumption and trade and the regional level.

3 Understanding Cassava Trading Networks

As previously mentioned, cassava is consumed both as a tuber and as its derivate products. The majority of cassava that enters the international market is in the form of less perishable, value-added commodities that are more readily transportable. These derived commodities include chips, starch, sweeteners and alcohol. As a commodity, cassava is partially substitutable for other commodities such as maize, wheat, rice and potato (but lacks the protein content of the first two).

As a traded carbohydrate, cassava has become increasingly globalized over time. In order to understand the dynamics of cassava, we first look at the evolution of the cassava trade at the global scale.

3.1 Evolution of the Cassava Trading Network

A number of factors have contributed to the evolution of cassava value chains and the international trade of the commodity. Cassava starch, for example, has evolved as a multibillion-dollar business worldwide, and is finding application in several industries. Cassava starch can perform most of the functions where maize, rice and wheat starch are currently used. Uses range from food to industrial (e.g., starch is utilized in sizing and dyeing in the textiles industries to increase brightness and weight of the cloth), to even the pharmaceutical industry where starch serves as a filler material and bonding agent for making tablets. In order to understand these dynamics, we have developed preliminary analyses of the cassava trading networks using network analytic approaches. Using COMTRADE data, we have developed analyses illustrate the relationship of trading partners and the relative power in terms of the individual countries relative to their trading partners. It is critical to note the evolution of trade patterns, with Thailand figuring as the most prominent exporter in both periods, and a dramatic shift in import patterns with China dominating the market (Figure 1). Also of note is the emergence of Vietnam and Cambodia as important exporters.

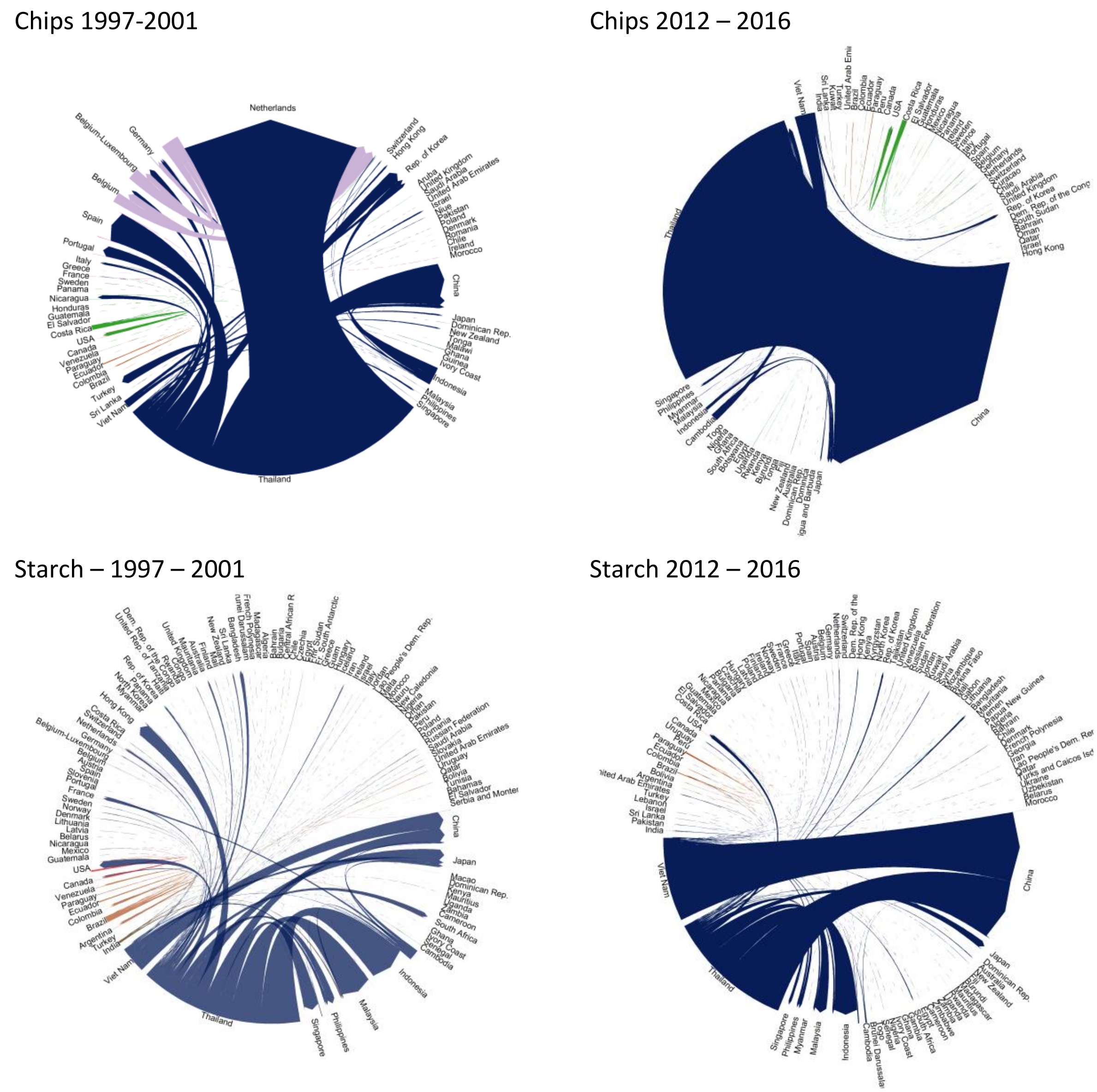

Figure 1: Evolution of cassava trading patterns

Although the cassava starch market shows a high level of dynamism, a network analysis of the global chips and starch trade suggests that the market, both in terms of production and consumption, is relatively consolidated (Figures 2-3). Southeast Asian countries dominate the export market and imports are heavily concentrated with a few countries. Such highly centralized networks tend to be vulnerable to shocks on either the production or the consumption side as illustrated in Wyckhuys et al. (2018).

Cassava chips 1997 | Cassava chips 2016

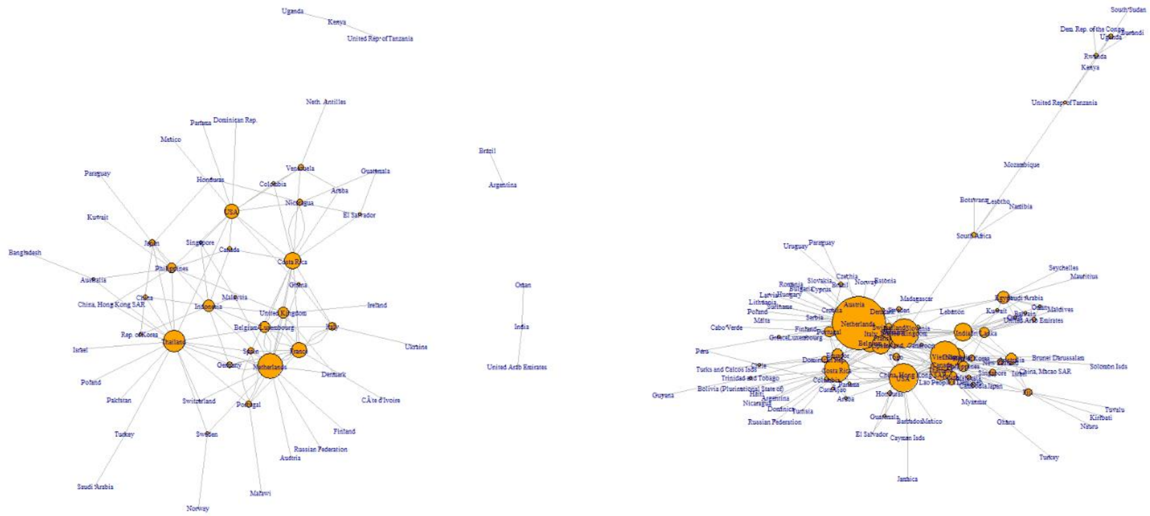

Figure 2: Trading networks of cassava chip. Node size is proportional to its number of trading partners.

Cassava starch 1997 | Cassava starch 2016

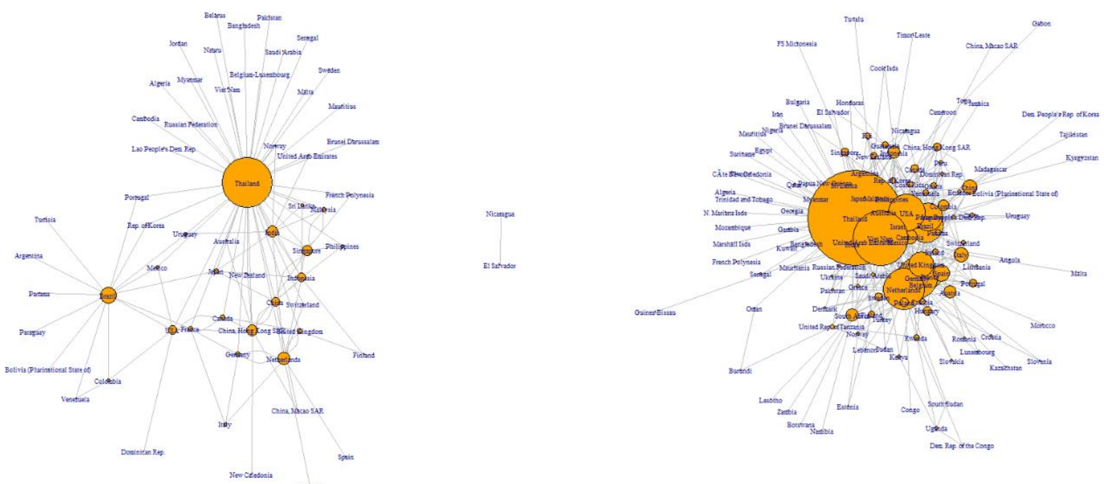

Figure 3: Trading networks of cassava starch. Node size is proportional to its number of trading partners.

3.2 Cassava in the Context of the Carbohydrate Market

In order to understand the dynamics of the cassava trade in greater detail, we conducted an analysis of the carbohydrate market, considering the global context but with a focus in SE Asia. In this study, we developed a principal component analysis to identify key price drivers and interactions in the carbohydrate market using FAO data. This includes a look at starch-based biofuel linkages with the petroleum market.

Starting from 63 price series of primary and secondary carb commodities across 7 countries in North America, South-east Asia, and China (Figure 4), we distilled five principle components (PCs) or trends in carbohydrate pricing (Figure 5). The first PC is essentially the average of the 63 price series, while PCs 2 through 5 capture the main forces defining the movements of the 63 price series. The PCs are numbered in order of their dominance, with PC2 being the most dominant trend, and subsequent PCs successively less influential.

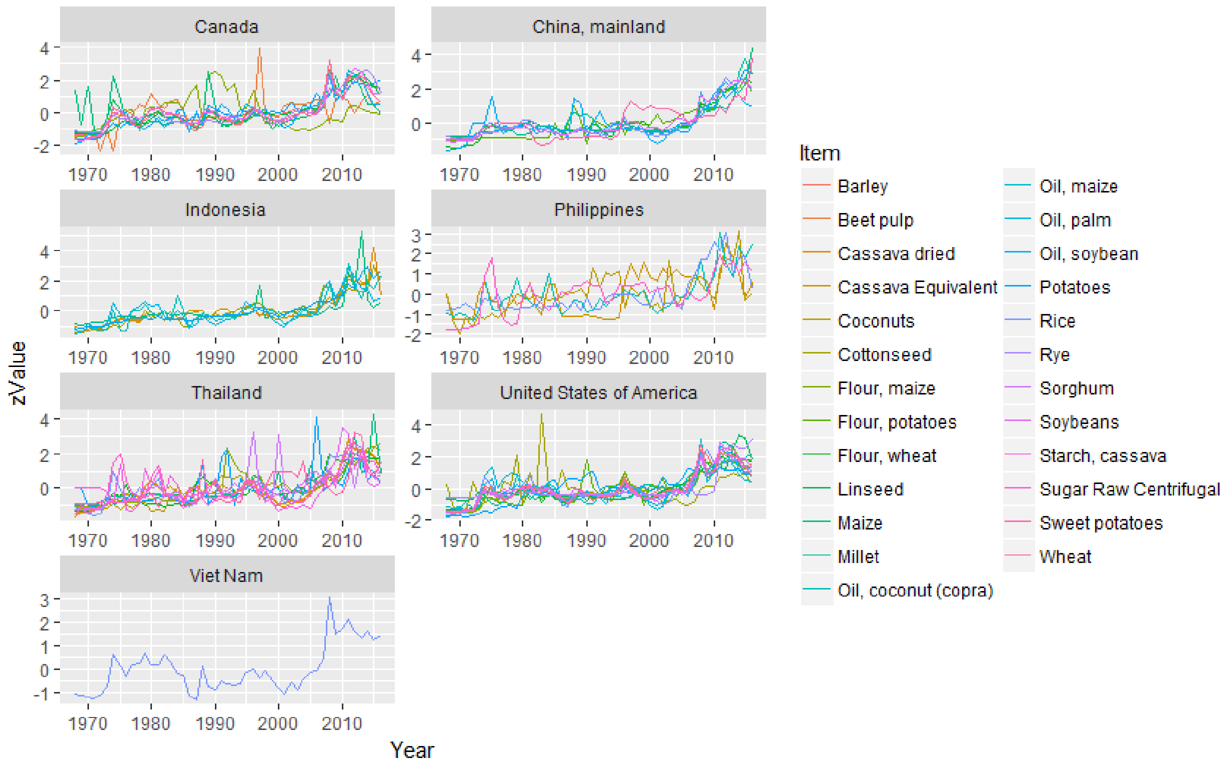

Figure 4: The 63 original price series on which PCA was performed

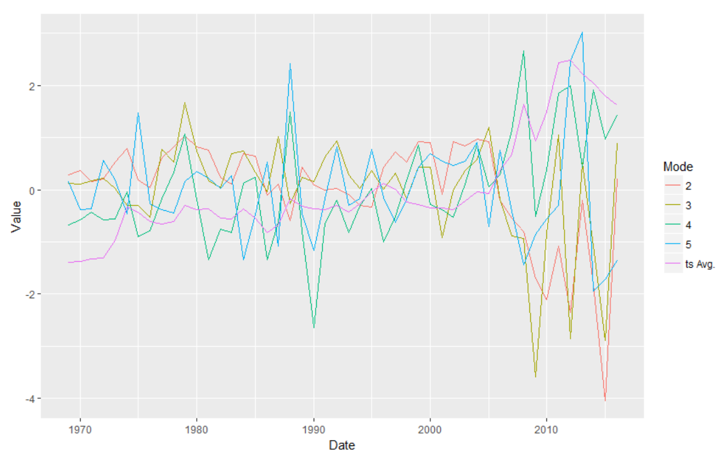

Figure 5: The four principle components to which the 63 original series were reduced, plotted together with the average

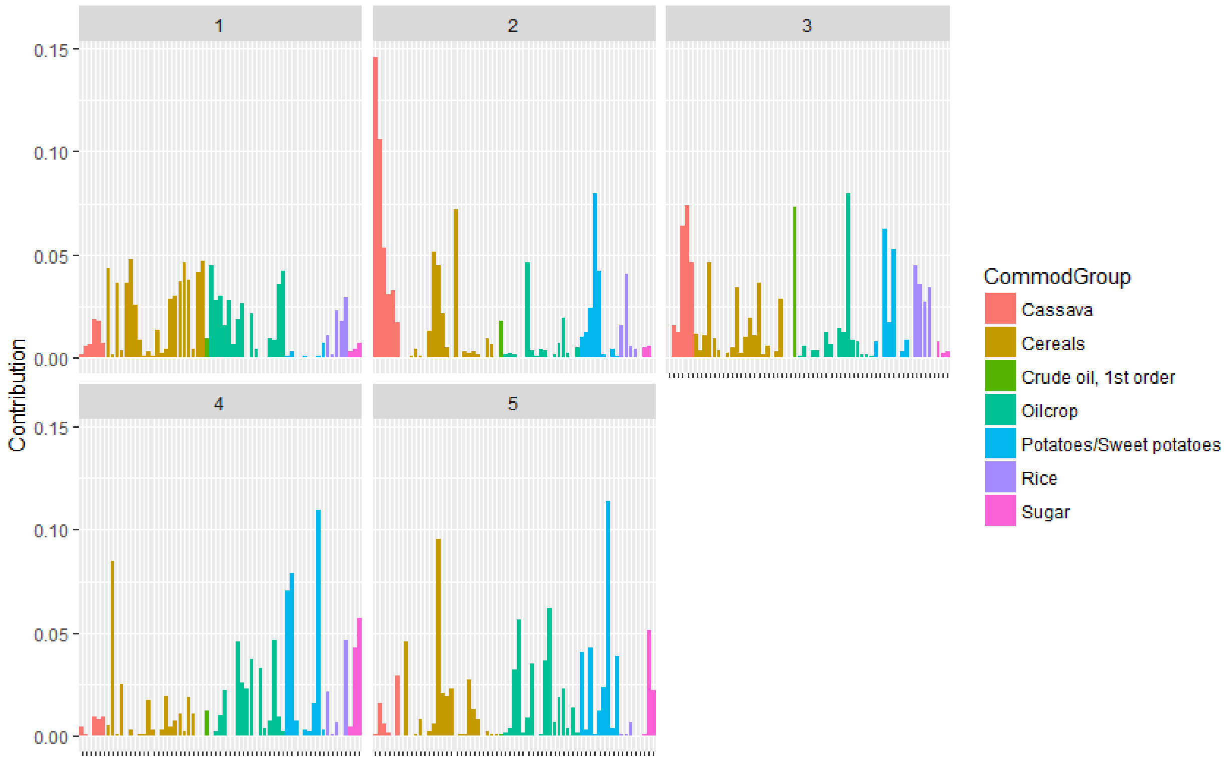

Figure 6: The contributions of the major carbohydrate groups to each of the principle components (PC). The main PCs are PC2-PC5. (PC1 just represents the average.) Note the cassava group's pronounced contribution to PC2 and PC3.

Analysis of the relative contributions of each commodity group to each of the four defining trends offers insight into which carbohydrate sources are the primary drivers of general price movements in the market (Figure 6). Cassava emerges from the analysis as the major contributor to the dominant component (PC2), followed by potatoes/sweet potatoes, and cereals. Cassava also figures prominently in the second most dominant component (PC3), together with oil crops, other potato/sweet potato products again, and first order movements[3] in oil price. These results suggest that cassava commodity movements play a fundamental role in shaping the entire carbohydrate market.

4 Characterizing Investment Potential using DEPE-Map

An interesting aspect of cassava is that there are many different ways in which cassava can contribute to economic activity. Ongoing research in multiple institutions examines how cassava might be bred, not only to help make cassava more resilient to pest and disease, but also to serve as a more efficient input as feedstock for industrial processes (e.g., manufacture of ethanol). The latter begs an important question, especially in the development context: What level of adoption of a "high tech" cassava would be sufficient to merit the investment in time and resources to develop the corresponding technology?

Here, we examine this question using a novel micro-economic model for ex-ante evaluation of potential cassava technologies. We evaluate supply curve shifts given a hypothetical research, release and uptake

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[3] I.e., changes in the *slope* of the oil price series. When the raw (0^{th} order) oil price was included in the analysis, it did not exhibit any contribution to the PCs.

of small granule cassava, and the resulting impacts on ethanol factory profitability for a hypothetical scenario based on parameters previously observed in Thailand.

The main aim here is to quantify the tradeoff between factory cost savings, on the one hand, and lower yields, on the other, that come with adoption of small granule cassava. The analysis identifies critical price thresholds at which adoption is profitable for both farms and factories. In doing so, we also identify which centiles of the farm yield distribution can be expected to adopt or not adopt (which could be used to conduct more efficient, highly targeted small granule cassava marketing campaigns).

4.1 Small granule ethanol study

In a 2016 Thai cassava ethanol (CE) factory trial, a switch to small granule cassava chip feedstock increased Simultaneous Liquefaction, Saccharification, and Fermentation (SLSF) ethanol production by 14% over the baseline cassava chip feedstock (Tranh 2016 pers. comm.). However, small granule cassava is also known to be lower yielding than the baseline cassava variety cultivated in Thailand. This means that farmers will not adopt small granule cassava unless CE factories pay them a sufficiently higher price to compensate for the yield loss relative to the baseline variety.

Whether or not it is profitable for CE factories to switch to small granule cassava therefore depends upon how high this premium is, and to what extent the added cost offsets the processing efficiency gain. Optimizing farmers likewise cannot decide whether to plant small granule cassava unless they have a reliable notion of the price they can expect to receive for the new product at harvest. In order to induce a coordinated supply response, it is therefore necessary to publicize timely estimates of the equilibrium small granule cassava root price. Failure to do so could result in an erratic supply, leading to scarcity or glut, with potentially dire consequences for farm and factory incomes.

Below, a map of such prices is calculated over a range of different combinations of farm yield loss and factory efficiency gain using DEPEMap. This is accompanied by maps of the total root production, ethanol output, mean farm and factory net revenue, adoption rate, and supply/demand market participation corresponding to each equilibrium price.

In a typical decision-making scenario, the planning agency would first examine 1) the mean factory net revenue map, 2) the mean farm net revenue map, 3) the supply market participation map, 4) the demand market participation map, and 5) the ethanol output map, in order to reach a decision as to whether the expected net benefit of the technology is high enough to justify its release and promotion. The definition of “net benefit” here depends upon the weight the planning agency gives to each of these five components.

If release and promotion of the new tech is deemed justifiable, then the planning agency would use the price map to determine the expected equilibrium small granule cassava root price. The planning agency would then publicize this price across the population of active and inactive cassava farms. Market forces take over from there to generate the corresponding root/ethanol production levels, mean farm and factory net revenues, adoption rates, and market participation shown on the respective maps.

The DEPEMap methodology used to generate these maps is explained below, followed by model parameterization. Before tackling the problem of small granule cassava, maps are presented for exogenous productivity changes that do not involve adoption, such as climate change. This intermediate step is taken to help build intuition about the model and the decision space.

4.1.1 Methodology: DEPEMap

Distributionally Explicit Partial Equilibrium Mapping (DEPEMap) is a new partial equilibrium model created by Ben Schiek of the DAPA Foresight Team at CIAT. It is intended to serve as an alternative to conventional parsimonious economic ex-ante impact assessment methods such as cost benefit analysis or the Economic Surplus Model. Whereas these conventional approaches assume arbitrarily shaped supply and demand functions, DEPEMap builds up supply and demand curves from their underlying distributions of factor endowments. DEPEMap is different from existing impact assessment models not because it makes new claims or modifications to existing theory, but because it is built up from an explicit application of the theory, in particular the microeconomic axioms of 1) firm/farm optimization, and 2) diminishing marginal returns to inputs.

DEPEMap moves beyond the conventional point estimate reporting format to instead present impacts in a map covering a wide range of parameter “coordinates”. The intention is to not only provide an answer to the client’s specific question, but also to transmit an intuition regarding the decision space in which they work. If the decision maker may be compared to a person looking for a particular object in a dark room, conventional point estimates are analogous to feeling around for the object in a limited part of the room. An impact map, on the other hand, is analogous to turning on the lights so that the decision maker may survey the entire contents of the room. See Appendix E for more details.

4.1.2 Parameterization

The DEPEMap status quo parameterization is presented in Table 10. These values are based on information presented by Sriroth et al. (2010), and unpublished cassava farm survey data collected by Tranh (2018 pers. comm.). The values given in these sources—which are based on the population of active producers—are then adjusted to reflect the population of both active and inactive producers before being fed into the model. Finally, values are fine tuned to produce an equilibrium root price and quantity that resembles the observed status quo (Figure 7). The graphs presented in the section above are based on the parameterization in Table 10.

Experts will note that the modeled status quo equilibrium root price of 1945 lcu/MT differs from the real status quo equilibrium root price of about 2500 lcu/MT. This is mostly because the real status quo price is determined by other sources of demand besides ethanol factories—such as starch factories and chips for export. In a real planning scenario, these other sources of demand should be taken into account.

Another potential source of inaccuracy is that demand side parameterization assumes a unimodal functional form for factory maximum capacity, whereas the information given by Sriroth et al. (2010) suggest that the distribution of factory maximum capacity is bimodal (with modes at 150 kL/day and 560 kL/day). DEPEMap can model multimodal distributions, but this would require more time and stakeholder involvement.

Table 10: DEPEMap status quo parameterization of the cassava root market

Parameter	Units	Value
Demand side		
Ethanol price	Lcu/kL	23500
Number of factories	Max demanding factories/day	33
Factory productivity	kL ethanol/MT roots	0.17
Mean processing cost	Lcu/kL ethanol	9000
CV processing cost	Dimensionless	0.08
Mean max. factory capacity	kL/day	298.9
CV logged max. factory capacity	Dimensionless	0.15
Supply side		
Number of farms	Max supplying farms/day	100
Mean farm cost per unit output	Lcu/MT root	1500
CV farm cost per unit output	Dimensionless	0.2
Max yield ceiling	MT/Ha.	45
Mean farm size	Ha.	1.25
CV logged farm size	Dimensionless	0.55
This parameterization yields the following status quo equilibrium		
Root price	Lcu/MT	1945
Root production (for ethanol)	MT/day	2421
Cassava ethanol production	kL/day	403.5
Supply side participation	Percent	91
Demand side participation	Percent	41
Mean farm net revenue	Lcu/Ha	9268
Mean factory net revenue	Lcu/day	359899

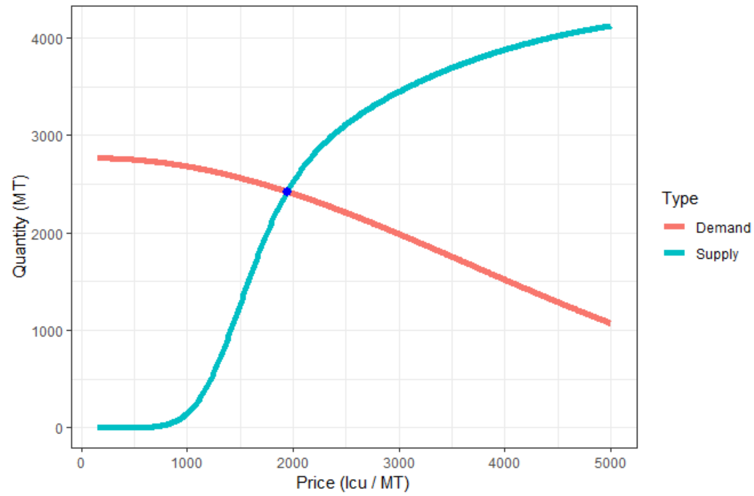

Figure 7: Status quo market equilibrium

4.1.3 Involuntary exogenous productivity changes

Before examining the case of small granule cassava, it is instructive to first examine the simpler case of involuntary exogenous shocks to farm and factory productivity. The term "involuntary shock" refers to any population-wide exogenous change which does not involve adoption. An example of such shocks is climate change, which exogenously alters farm productivity whether the farmers like it or not. One could say adoption is "forced" in such cases. On the demand side, involuntary exogenous shocks might take the form of government imposed operating requirements, or technological innovations that cost nothing to implement. These maps could be useful to a planning agency in developing outlooks for different climate change impact and technological/policy mitigation scenarios. Market equilibria corresponding to various scenarios of involuntary exogenous shocks to supply and demand side productivity are plotted in Figure 8.

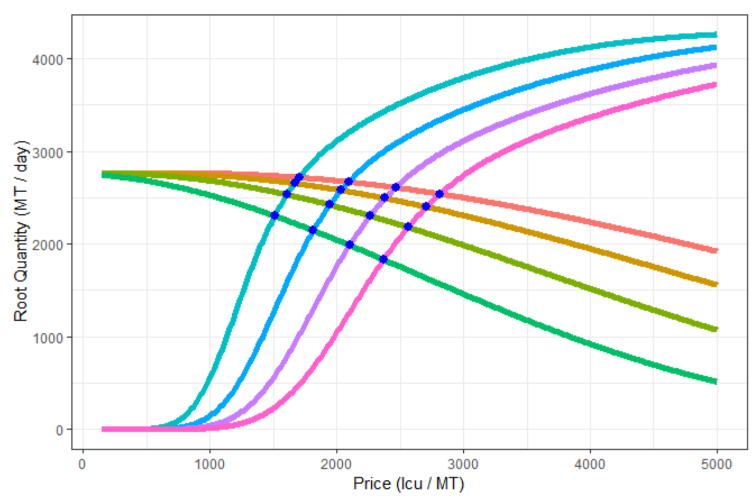

Figure 8: Multiple equilibria resulting from hypothetical involuntary exogenous productivity shocks on both the demand and supply side.

4.1.3.1 Impact maps, involuntary adoption

A map is presented in Figure 9 indicating the equilibrium price to be expected given a wide range of potential combinations of involuntary exogenous shocks to demand and supply productivity. In this map, the new factory productivity resulting from the demand side shock is indicated along the bottom x-axis. The new farm cost resulting from the supply side shock is indicated along the left y-axis. The top x-axis and right y-axis indicate the corresponding percentage change over the status quo value. Note that both positive and negative percentage changes are covered in the map. The status quo scenario is therefore located at the center of the map. The color scale is gradated such that the yellow hue corresponds to the status quo price.[4]

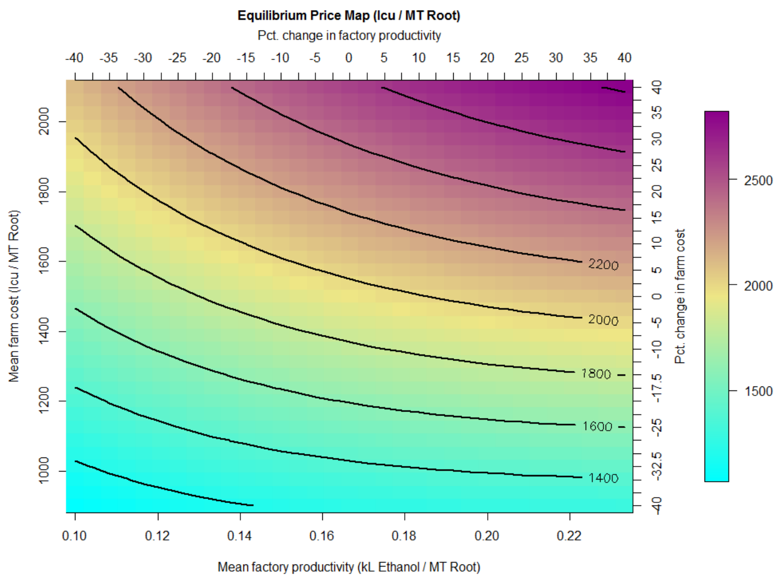

Figure 9: Equilibrium price map, involuntary exogenous demand and supply productivity shocks

Maps of the cassava root and ethanol production levels are likewise presented in Figure 10. Again, in each map, the yellow hue corresponds to the status quo value.

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[4] In this study, the focus is on shocks to farm cost and factory productivity; but maps showing price, quantity, etc., for shocks to factory maximum capacity, farm yield ceiling, or any of the other parameters in Table 10 may also be examined.

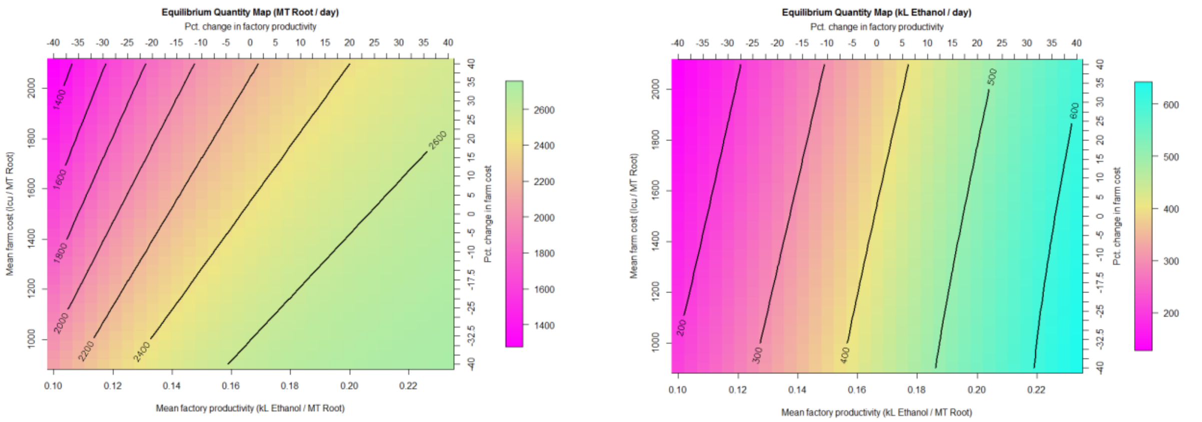


Figure 10: Equilibrium root and ethanol output maps, involuntary exogenous demand and supply productivity shocks

Maps of farm and factory net revenue are presented in Figure 11, while maps of the market participation levels corresponding to each scenario are presented in Figure 12. These four maps should be considered together in order to develop an idea of the welfare impact of each exogenous involuntary shift scenario.

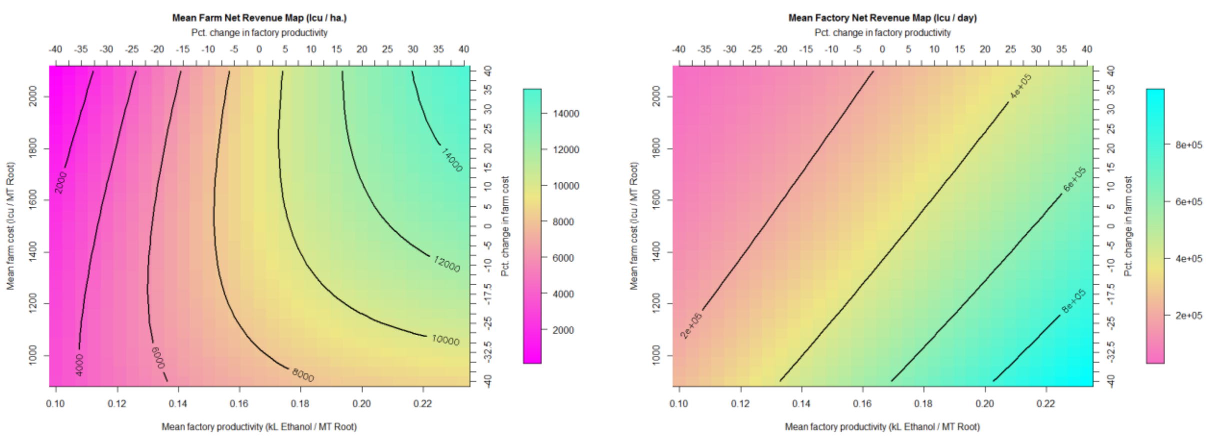


Figure 11: Farm and factory net revenue maps, involuntary exogenous demand and supply productivity shocks

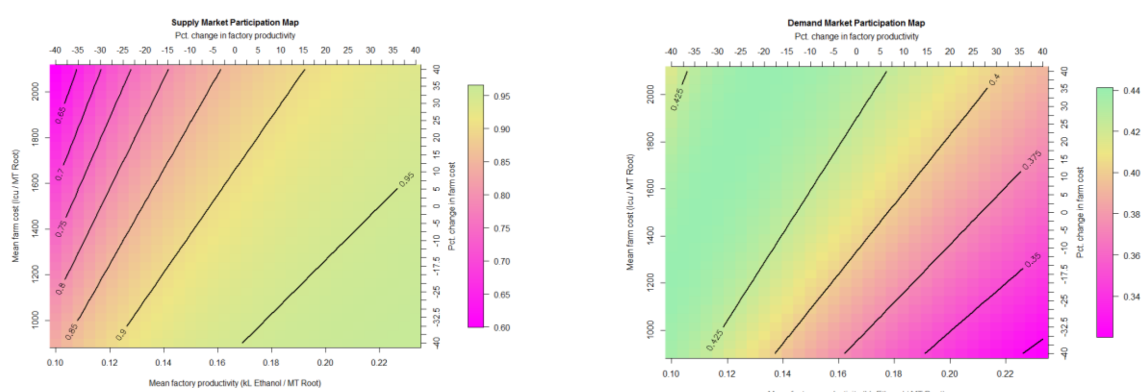


Figure 12: Farm and factory participation maps, involuntary exogenous demand and supply productivity shocks

4.1.4 Voluntary adoption of small granule cassava

The case of small granule cassava is considerably more complicated than the scenarios mapped out above since it involves the question of voluntary adoption. This is a case of voluntary exogenous impact, where the overall impact is contingent upon farmers and factories choosing to adopt the exogenous change.

Even as voluntary exogenous impact assessments go, this one poses a unique challenge. Typically, such studies focus on the cost-benefit tradeoff of adopting a new technology that alters productivity on *either* the supply or demand side, whereas release and uptake of small granule cassava would imply simultaneous changes to productivity on both the demand and supply side. Moreover, there is no cost-benefit tradeoff question inherent in the new technology itself. That is, from a purely technological standpoint, adoption of small granule cassava would be unambiguously detrimental for farmers and unambiguously beneficial for factories. The question of a cost-benefit tradeoff only arises when the market is taken into consideration. Can the demand side benefits of small granule cassava generate market conditions under which farmers can be convinced to adopt a lower yielding variety?

The greater complexity of voluntary exogenous impacts can be appreciated in Figure 13, depicting small granule, baseline, and composite cassava root market equilibria across a range of supply and demand side voluntary exogenous productivity shifts.

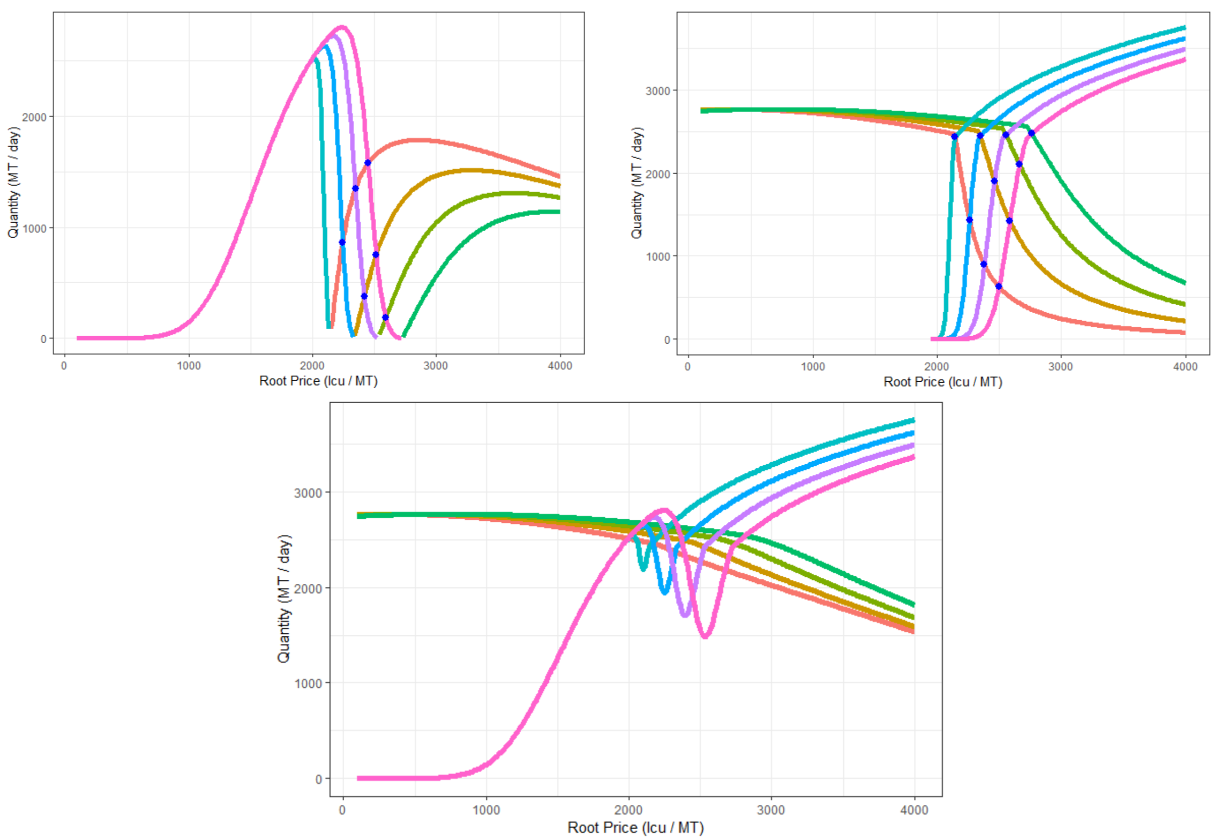


Figure 13: Cassava root equilibria under voluntary exogenous shocks for (clockwise from top left) the small granule, baseline, and composite markets.

4.1.4.1 *Endogenously modeled adoption rates*

Impact studies abound with vexation over adoption rates—how to estimate them, why they tend to be so low, how to raise them, and so forth. The creation of DEPEMap is largely motivated by the need for a more careful treatment of these open problems than is currently offered by conventional models. Whereas most conventional methods take adoption rates as an exogenous input (determined by "expert opinion", for example), in DEPEMap adoption rates are modeled endogenously.

Explicit consideration of the entry and exit of farms into production complicates the conventional treatment of adoption rates. In the conventional treatment, adoption rates are conceived as the percentage of the producing population who switch to the new technology. However, since farms enter/exit production in reaction to any change in price or productivity, the "producing population" is itself a moving target. Adoption rates might be high not because of high uptake, but merely because of a significant exit of farms from the producing population. Conversely, a low adoption rate may be the result not of low uptake, but rather of significant entry of farms into the market.

The release of a new technology that may be voluntarily adopted by farmers generates two supply curves—one for the baseline technology and one for the new technology (Figure 14). Adoption of the new technology occurs over a limited price range defined by the dashed lines. Below this range, adoption is 0%; and above it, adoption is 100%. The composite supply curve (i.e. the sum of the alternative and baseline supply curves) is given in Figure 15. Note that market participation does not necessarily increase with adoption rate (Figure 16). The factory side analogues of Figures 14-16 are given in Figure 17.

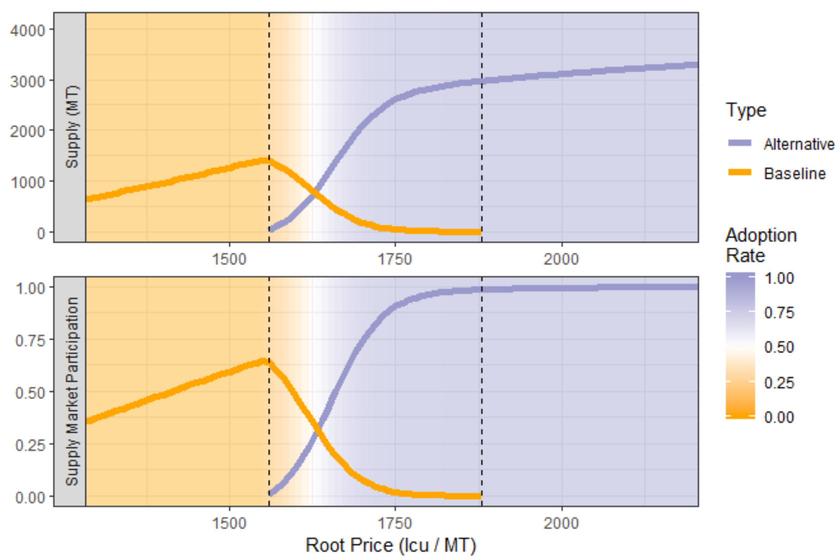


Figure 14: Supply and farm participation curves for baseline and small granule cassava. In this case it is assumed that small granule cost per unit output is 20% higher than the baseline.

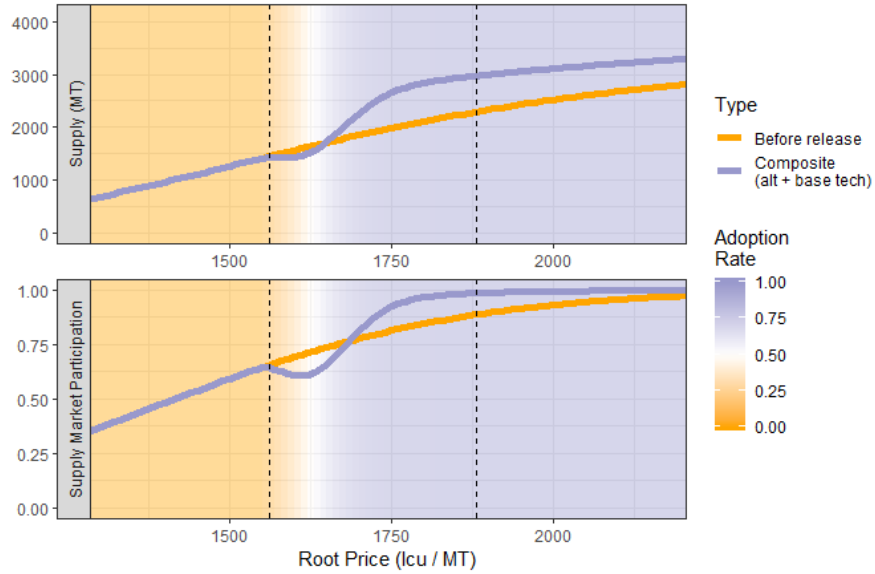


Figure 15: Composite supply and farm participation curves. These curves aggregate the baseline and small granule curves in the previous figure.

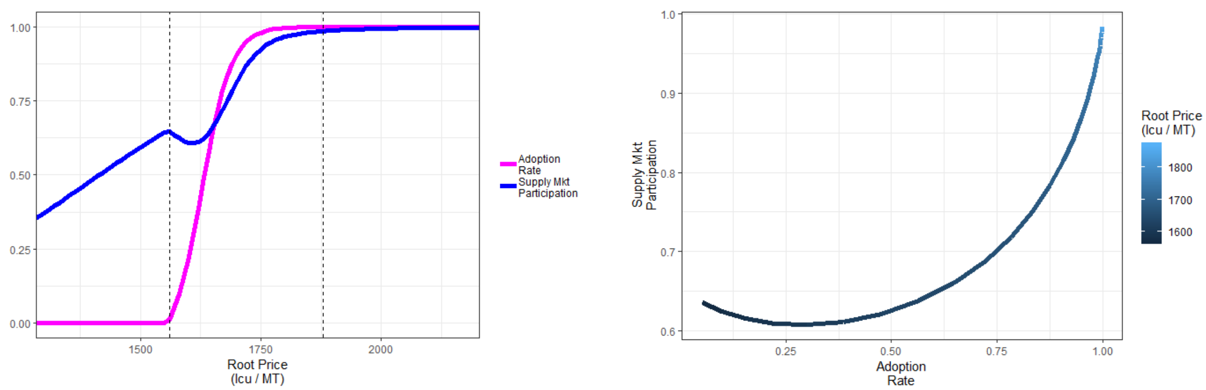
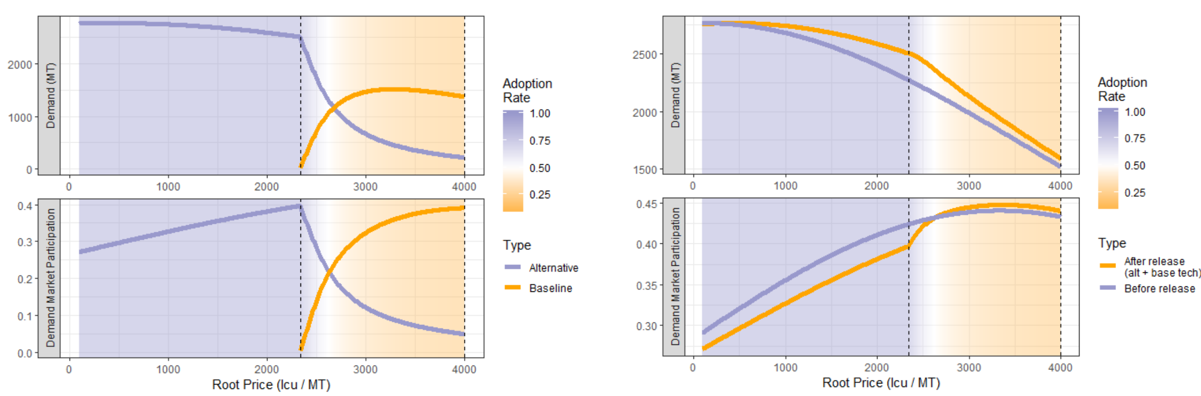


Figure 16: Small granule farm adoption rate compared against farm participation for the case where small granule cost per unit output is 20% higher than the baseline. Note that farm participation does not necessarily increase with adoption rate.



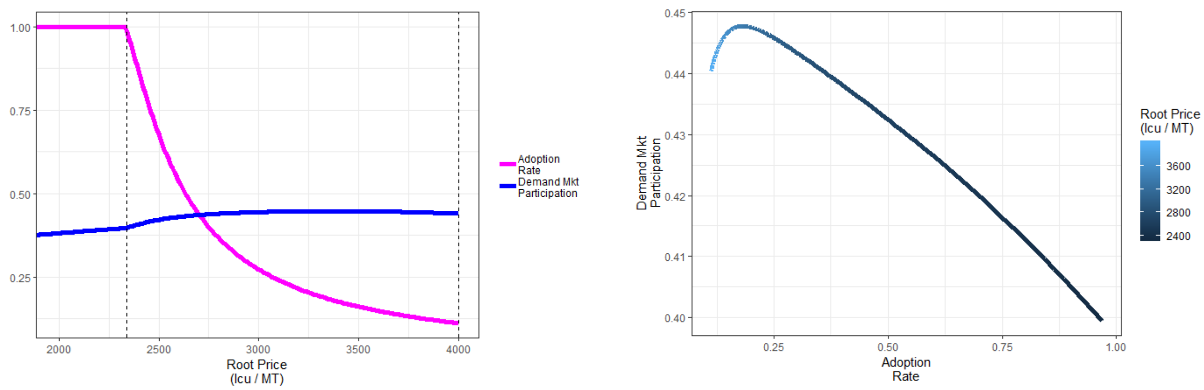


Figure 17: (Clockwise from top left) a) Demand and factory participation curves for baseline and small granule cassava, b) Composite demand and factory participation curves, c) & d) Small granule factory adoption rate compared against market participation. All graphics illustrate the case where ethanol output per unit root is 20% higher than the baseline. Note that market participation does not necessarily increase with adoption rate.

4.1.4.2 Impact maps, voluntary adoption

Price maps of the baseline and small granule cassava root markets are presented in Figure 18. Note that, unlike the involuntary maps—which examined generic exogenous shocks—these maps only cover changes in farm cost and factory productivity that are within the expected range for the specific case of small granule cassava. Hence, only positive percentage changes are examined, up to 40%. The status quo scenario is therefore located at the lower left corner of the map. Once again, the yellow hue corresponds to the status quo value.

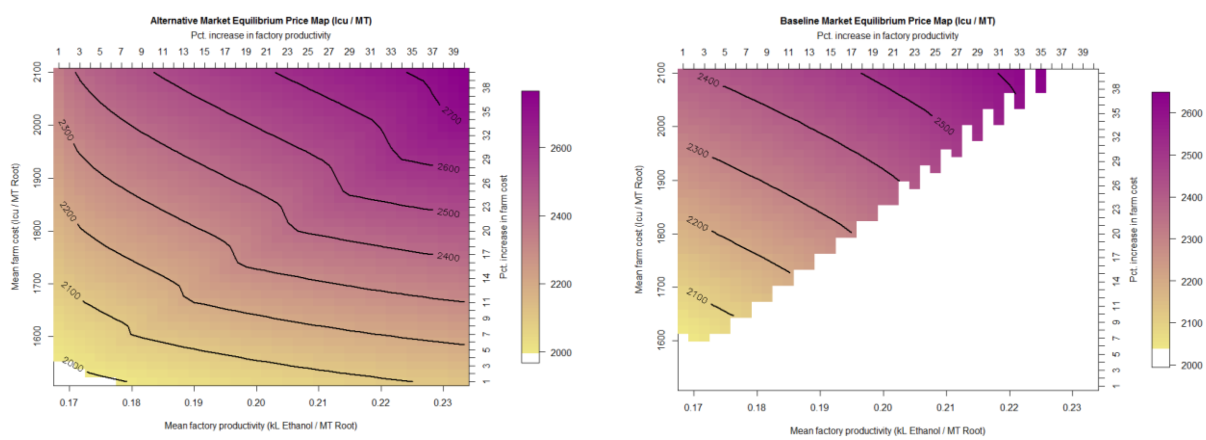


Figure 18: Alternative and baseline market equilibrium price maps, voluntary exogenous supply and demand productivity shocks. Blank areas correspond to cases where the market fails to clear (the supply and demand curves fail to intersect).

When adoption is voluntary, the price map takes on added importance. It becomes not just an impact report, but rather an essential instrument in achieving the impacts indicated on the map. That is, the planning agency must publicize the indicated price at the coordinates of the expected increase in farm cost and factory productivity far in advance of harvest in order for the market to clear at that price. This is because the adoption rate is a key determinant of supply and hence of price; and farmers will not know whether to adopt or not unless they have a clear idea of the price they can expect to receive at harvest.

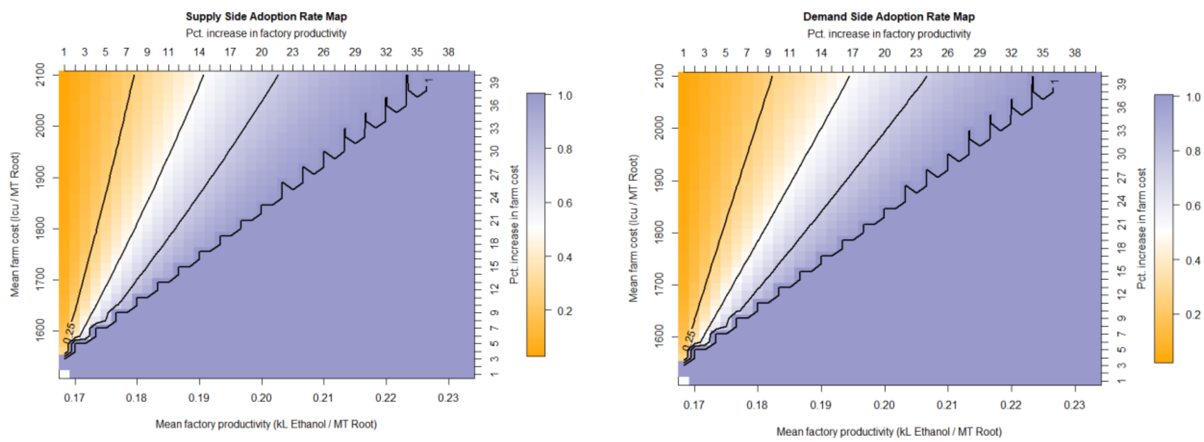


Figure 19: Supply and demand adoption rate maps. The white hue corresponds to 50% adoption.

The supply side adoption rate map (Figure 19) indicates that, at the expected 14% cassava ethanol factory productivity increase, farmer adoption of small granule cassava would be greater than 50% so long as the associated farm cost due to yield loss is less than about 2100 lcu/MT (a 40% increase over the baseline farm cost). Adoption would be 100% so long as farm cost is less than about 1750 lcu/MT (a 15% increase over the baseline farm cost). On the demand side, factory adoption of small granule cassava feedstock is greater than 50% at the expected productivity increase for all farm costs lower than about 1950 lcu/MT (a 30% farm cost increase), and 100% for all farm costs lower than about 1750 lcu/MT (a 15% farm cost increase).

Meanwhile, the aggregate market participation maps in Figure 20 indicate that overall demand market participation would not diverge much from the status quo rate of 41% in any scenario.[5] Supply market participation could increase (at the expected factory productivity increase) by up to 5 percentage points (pp) above its status quo of 91% if the increase in mean farm cost does not exceed about 15% (1700 lcu/MT). For scenarios in which the farm cost increase exceeds this value, supply market participation begins to decline considerably. A 40% farm cost increase would result in a roughly 12 pp reduction in farmer participation.

[5] See Appendix F for demand and supply market participation maps disaggregated by technology.

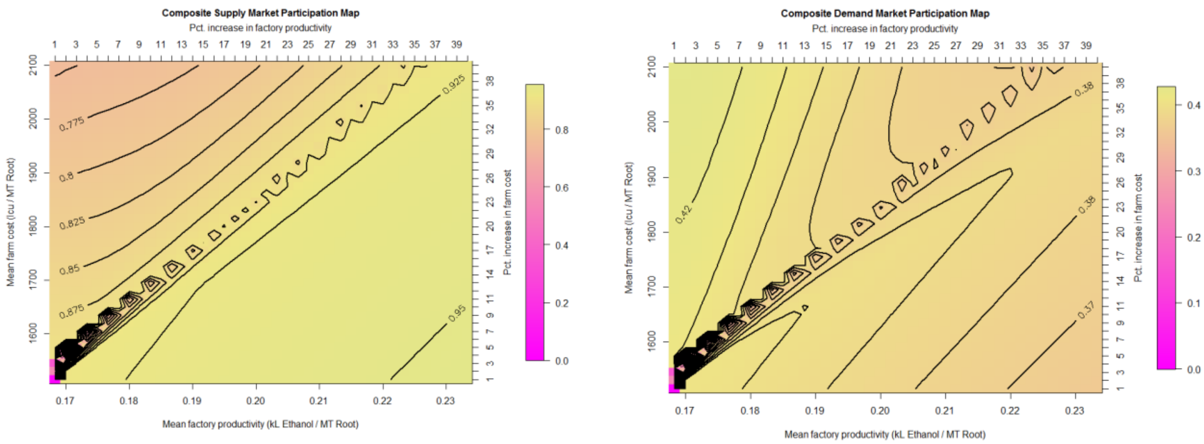


Figure 20: Farm and factory aggregate market participation maps, voluntary exogenous supply and demand productivity shocks

Root and ethanol aggregate production maps are presented for the small granule and baseline markets in Figure 21.[6] These maps suggest that total cassava root production for ethanol would increase 100-300 hundred MT/day above the status quo of 2421 MT/day for scenarios in which the farm cost increase is under 18%, and decrease by a similar amount for scenarios in which the farm cost increase is above this threshold. This translates into increases in cassava ethanol production of up to 80 kL/day over the status quo of 404 kL/day for farm cost increases less than 18% and little to no decrease in ethanol output for farm cost increases above this threshold.

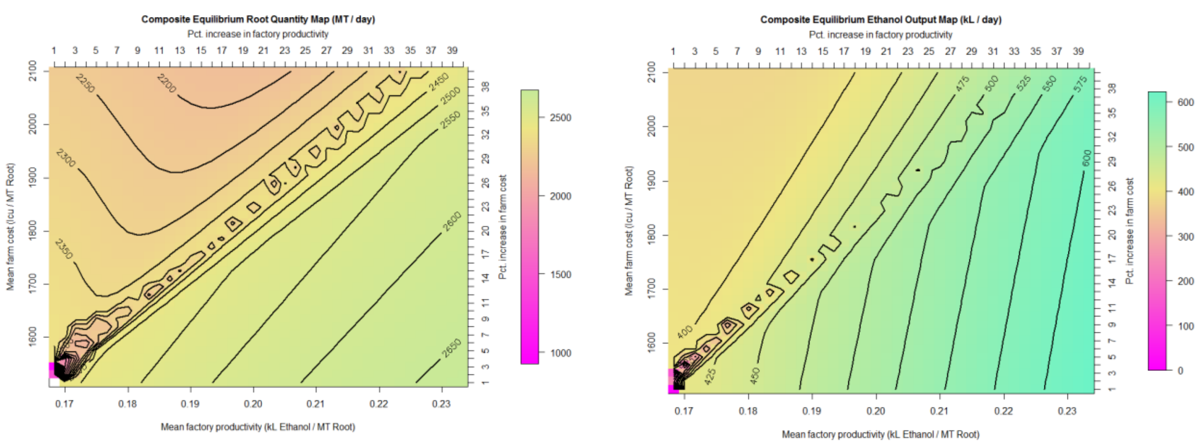


Figure 21: Root and ethanol aggregate output maps, voluntary exogenous supply and demand productivity shocks

Farm and factory mean net revenue maps are presented in Figure 22 for the small granule and baseline markets. These maps suggest that mean net revenue on adopting farms would increase by up to 3000 lcu/ha. over the status quo of 9268 lcu/ha. for scenarios in which the farm cost increase is less than 30%. On non-adopting farms, the mean net revenue would also rise slightly for farm cost increases under this threshold. For scenarios in which the farm cost increase is greater than 30%, mean net revenue would decrease by up to 3000 lcu/ha. on adopting and non-adopting farms. On the demand side, the mean net revenue would increse by up to 1000000 lcu/day and 250000 lcu/day over the baseline of 359899

[6] See Appendix F for root and ethanol output maps disaggregated by technology.

lcu/day at adopting and non-adopting factories, respectively, for scenarios in which the farm cost increase is under 30%. Above this threshold, the mean net revenue would decrease at both adopting and non-adopting factories by about 500000 lcu/day.

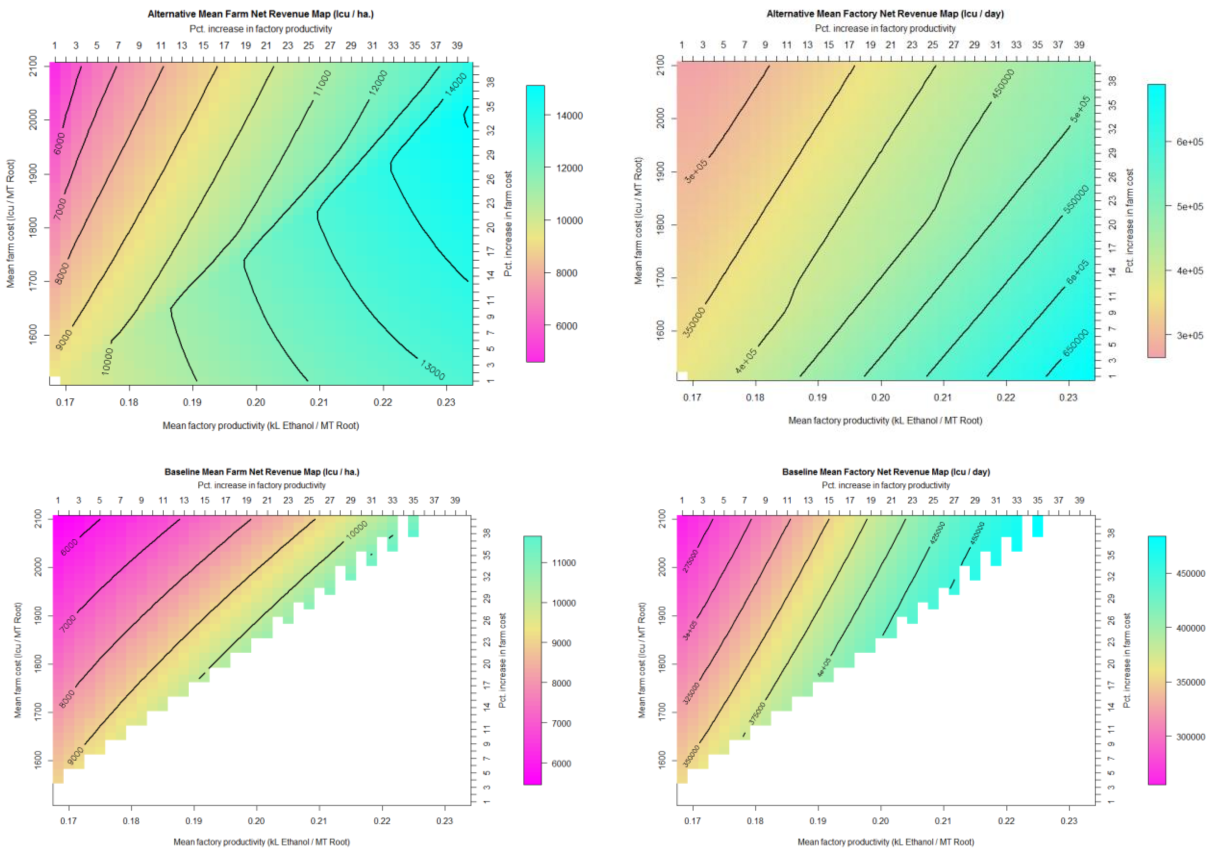


Figure 22: (Top) Small granule farm and factory net revenue maps, (bottom) baseline variety farm and factory net revenue maps. The blank parts of the baseline market maps correspond to scenarios in which adoption of small granule cassava is 100%.

4.1.5 Small granule cassava study conclusion

Given the 14% increase in ethanol productivity achieved in the 2016 Thai SLSF factory trial, DEPEMap modeling suggests that release of small granule cassava would result in high farm adoption (>50%) so long as the associated increase in mean farm cost due to yield loss is not greater than 40% over the status quo of 1500 lcu/MT. The model suggests 100% adoption across scenarios with a farm cost increase of 15% or lower. However, high adoption does not necessarily mean high market participation. Up to the 100% adoption threshold, overall supply market participation could fall by as much as 12 pp below the status quo of 91%. Above the 100% adoption threshold (corresponding to scenarios in which the farm cost increase is under 15%), supply market participation would remain the same or increase by a few percentage points. On the demand side, DEPEMap suggests high uptake for scenarios in which the mean farm cost increase is less than 30%, with overall factory participation diverging little from the status quo of 41% across all scenarios.

Total cassava root production for ethanol would increase by up to 300 MT/day for scenarios in which the farm cost increase is less than 18%, translating into a an increase in ethanol production of up to 80 kL/day over the status quo of 404 kL/day. Root production would fall below the status quo in scenarios where the farm cost increase exceeds the 18% threshold, but this would not translate into a proportional fall in cassava ethanol output, which would remain close to the status quo level in such scenarios.

The mean farm net revenue would increase on both adopting and non-adopting farms so long as the farm cost increase does not exceed 30%, but decrease otherwise. Likewise, mean factory net revenue would increase at both adopting and non-adopting factories for scenarios in which the farm cost increase is less than 30%, and decrease otherwise.

Overall, then, three critical farm cost increase thresholds emerge from this study: 1) A threshold at 15%, above which supply market participation begins to decrease beneath the status quo, 2) a threshold at 27%, beneath which ethanol output increases above the status quo, and 3) a threshold at 30%, above which mean farm and factory net revenues turn negative. These thresholds reduce to roughly 10%, 18%, and 20%, respectively, if the expected small granule factory productivity gain turns out to be 10% instead of 14%. Remarkably, the maps suggest no downside to small granule release in terms of ethanol output. Root production could fall in some high farm cost scenarios, but this is apparently offset by the higher factory productivity. On the other hand, the ethanol production upside is modest, with a maximum increase of about 80 kL/day over the status quo in low farm cost scenarios.

There are numerous ways in which this study could be refined. In particular, greater stakeholder involvement could improve the parameterization by more accurately modeling the bimodal demand market, chip market, and the potential role that credit could play in achieving specific production and welfare targets.

5 Summary and Conclusion

Cassava is an interesting crop with global important and relevance for a number of reasons:

- The crop is key in a diverse set of next use contexts.
- Climate change is affecting the crop around the world, concentrating production and demand and shifting both production and demand from their historical patterns.
- The crop fits various socioeconomic contexts, from a subsistence crop to a source for highly specialized starches.
- The trading networks have evolved rapidly, but this evolution has potentially concentrated both production and demand on the global landscape.
- The concentration of both cassava production and use has the potential to have significant economic implicating if there is either a policy shock or a biophysical shock to the system.

The latter issue, the concentration of the production and consumption networks, is emphasized in a paper published in related to this work:

> Wyckhuys, K. A., Zhang, W., Prager, S. D., Kramer, D. B., Delaquis, E., Gonzalez, C. E., & Van der Werf, W. (2018). Biological control of an invasive pest eases pressures on global commodity markets. Environmental Research Letters, 13(9), 094005.

See: https://doi.org/10.1088/1748-9326/aad8f0

As with many commodity crops, the future of cassava offers both prospects and risks. With the various analyses presented here, we illustrate some of the potential pressures at the global scale, the dynamics of in terms of the global markets and corresponding evolution of trade networks, the role of cassava in influencing overall carbohydrate price trends, and the feasibility of specific cassava technology under different market conditions.

We apply some of this understanding the analysis published in Wyckhuys et al. and show both the economic risk and potential value of biological control solutions.

Our key observation in this work is that cassava is, indeed, a highly valuable commodity with a lot of potential. We need to be selective about our approach to cassava as a development intervention, and focus on holistic solutions. These solutions must address climate other biophysical pressures, prioritize key geographies for interventions, develop appropriate technologies for appropriate places, reduce production costs, and consider policy action where feasible.

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Appendix

A. Production by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP2	RCP8.5_SSP3
Cambodia	0.647	0.686	0.667	0.512
Philippines	2.091	2.123	3.773	3.498
Thailand	0.059	0.099	0.608	0.512
Vietnam	-2.773	-2.743	-3.543	-4.170
Brazil	-6.886	-6.833	-8.001	-9.453
Colombia	6.270	6.329	7.397	6.794
Costa Rica	-3.202	-3.143	-3.115	-2.982
Paraguay	-9.512	-9.475	-15.634	-17.173
India	-3.745	-3.646	-5.528	-6.145
Angola	-8.443	-8.342	-10.195	-11.353
Cameroon	-5.903	-5.883	-6.886	-7.867
Kenya	4.588	4.649	1.742	0.811
Mozambique	-6.470	-6.432	-4.469	-4.949
Nigeria	-2.447	-2.387	-2.136	-3.453

B. Yield by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP2	RCP8.5_SSP3
Cambodia	-0.135	-0.121	-0.096	-0.511
Philippines	1.342	1.353	3.011	2.527
Thailand	-0.763	-0.747	-0.203	-0.538
Vietnam	-3.215	-3.204	-3.710	-4.530
Brazil	-6.118	-6.108	-6.764	-8.307
Colombia	5.111	5.127	6.407	5.580
Costa Rica	-3.700	-3.685	-3.524	-3.656
Paraguay	-8.937	-8.923	-13.958	-15.470
India	-4.469	-4.447	-5.645	-6.558
Angola	-7.667	-7.653	-8.565	-10.128
Cameroon	-6.289	-6.274	-6.901	-8.083
Kenya	3.715	3.739	2.088	0.786
Mozambique	-6.626	-6.603	-4.198	-4.979
Nigeria	-2.796	-2.781	-2.218	-3.739

C. Demand by 2050

Region	RCP4.5_SSP2	RCP4.5_SSP3	RCP8.5_SSP2	RCP8.5_SSP3
Cambodia	-1.008	-1.031	-1.001	-1.490
Philippines	-1.266	-1.281	-1.306	-1.878
Thailand	-0.913	-0.955	0.320	-0.215
Vietnam	-9.505	-9.229	-12.707	-13.983
Brazil	-4.366	-3.987	-6.562	-8.512

Colombia	-1.589	-1.523	-1.803	-2.356
Costa Rica	-0.590	-0.607	-0.550	-0.834
Paraguay	-3.216	-3.094	-3.806	-5.079
India	-1.278	-1.307	-1.254	-1.878
Angola	-2.563	-2.577	-2.650	-3.821
Cameroon	-2.252	-2.253	-2.341	-3.292
Kenya	-2.252	-2.309	-2.271	-3.397
Mozambique	-2.312	-2.346	-2.364	-3.461
Nigeria	-3.110	-3.040	-3.598	-4.842

D. Net trade by 2050

Region	**RCP4.5_SSP2**	**RCP4.5_SSP3**	**RCP8.5_SSP2**	**RCP8.5_SSP3**
Negative				
EAP-Cambodia	-6.092	-4.994	-6.123	-6.113
EAP-Philippines	-12.127	-9.070	-17.740	-14.183
SAS-India	5.043	3.572	9.696	7.022
SSA-Kenya	-28.025	-18.655	-17.391	-13.284
SSA-Mozambique	3.908	4.092	0.785	-1.115
SSA-Nigeria	-21.068	-20.071	-43.519	-41.255
Positive				
EAP-Thailand	1.097	1.052	0.916	1.169
EAP-Vietnam	0.409	-0.032	0.789	-0.067
LAC-Brazil	-22.545	-19.583	-16.941	-13.667
LAC-Colombia	31.179	38.761	36.558	44.591
LAC-Costa Rica	-3.357	-3.299	-3.266	-3.117
LAC-Paraguay	-16.996	-16.150	-29.693	-29.823
SSA-Angola	-21.385	-22.143	-26.793	-29.390
SSA-Cameroon	-16.361	-15.705	-19.907	-20.243

E. Distributionally explicit supply and demand modeling using DEPEMap

DEPEMap builds up supply and demand from the underlying production distribution. This distributionally explicit construction forces into view several basic facts of economic life that are overlooked—and often contradicted—by conventional models, most importantly:

- Farms enter and exit the market based on their productivity and on market price. In DEPEMap, the "farm population" therefore includes farms that are actively producing, but that could leave the market given a rise in price (or decrease in productivity); as well as farms that are not producing but that could enter the market given an appropriate fall in price (or increase in productivity). A supply curve built up from these considerations is highly non-linear and has constantly changing elasticity, contrary to conventional assumptions (Figure 23).

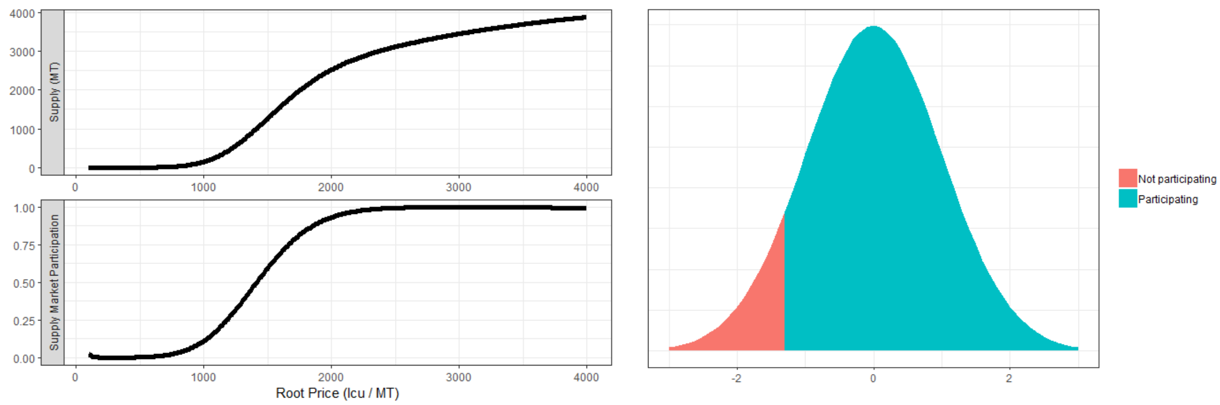
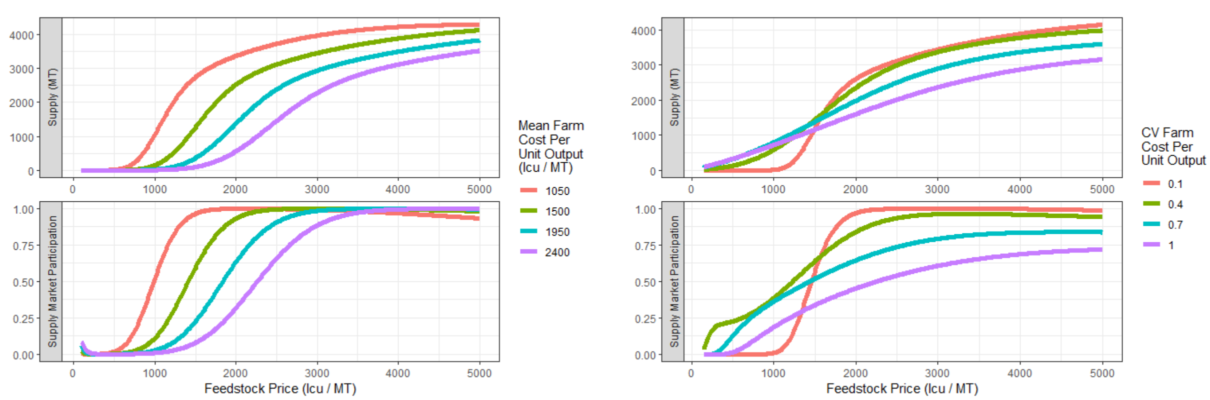


Figure 23: (Left) Supply curve together with the farm market participation curve. (Right) Participation at a specific price along the supply curve.

- There is no "representative farm", as assumed in the conventional approaches. The distribution of factor endowments—i.e. farm size, soil quality, equipment, access to markets, risk capital, etc.—is typically very inequitable. The best growing conditions tend to be concentrated among a few large farms, while most farms are small and resource-poor. The inequitable distribution can be modeled by a skewed functional form such as the lognormal distribution. The shape of the supply curve then depends critically upon the parameters (mean and coefficient of variation) of this distributional form. DEPEMap facilitates exploration of how changes in the parameters of these underlying distributions affect the supply curve (Figure 24).
- This forces into view the much neglected influence of *how equitably the impact is distributed across the population*—as measured in the standard deviation or coefficient of variation (CV)—on supply and market participation. Planners and researchers tend to focus on mean values; and conventional models reinforce this tendency. In Figure 24, on the other hand, DEPEMap reveals that greater equality in the distribution of key parameters can increase supply just as well as an increase in the mean. Moreover, it shows that greater equality also goes hand in hand with greater market participation, whereas the same is not necessarily true for an increase in the mean.



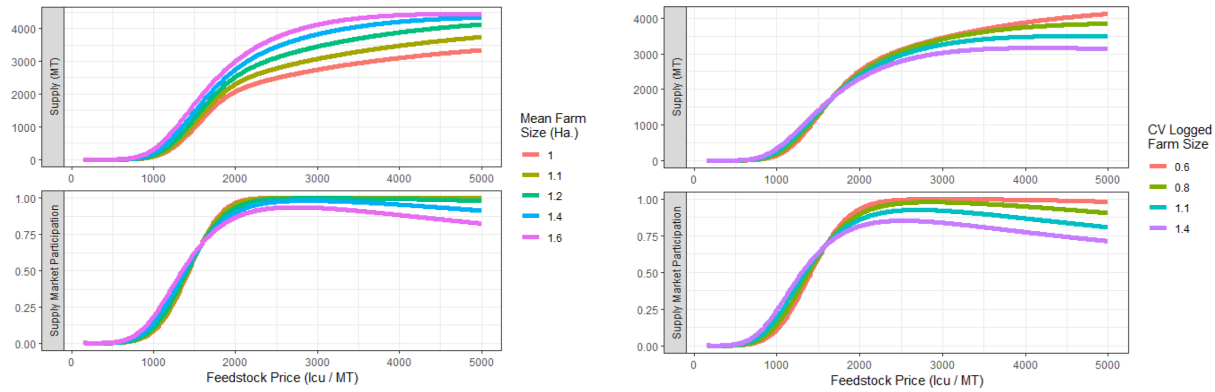


Figure 24: Supply and farm market participation curve sensitivity to changes in key parameters

- All of the forgoing applies to the demand side (Figures 25-26). There is also an adoption rate on the demand side whenever the new technology implies a qualitative change in product traits from the buyer's (households, factories, exporters, speculators, etc.) perspective. Such traits may include, for example, flavor, appearance, nutrient/chemical content, cooking time, palatability, processability, etc. In the case of small granule cassava, factories are interested in adopting the new technology because of enhanced processability.

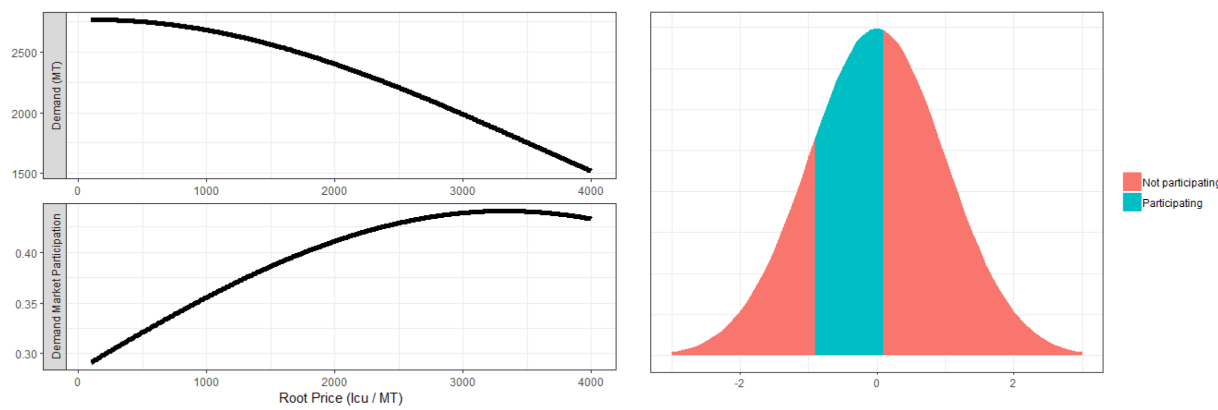


Figure 25: (Left) Demand curve together with the factory market participation curve. (Right) Participation at a specific price along the demand curve.

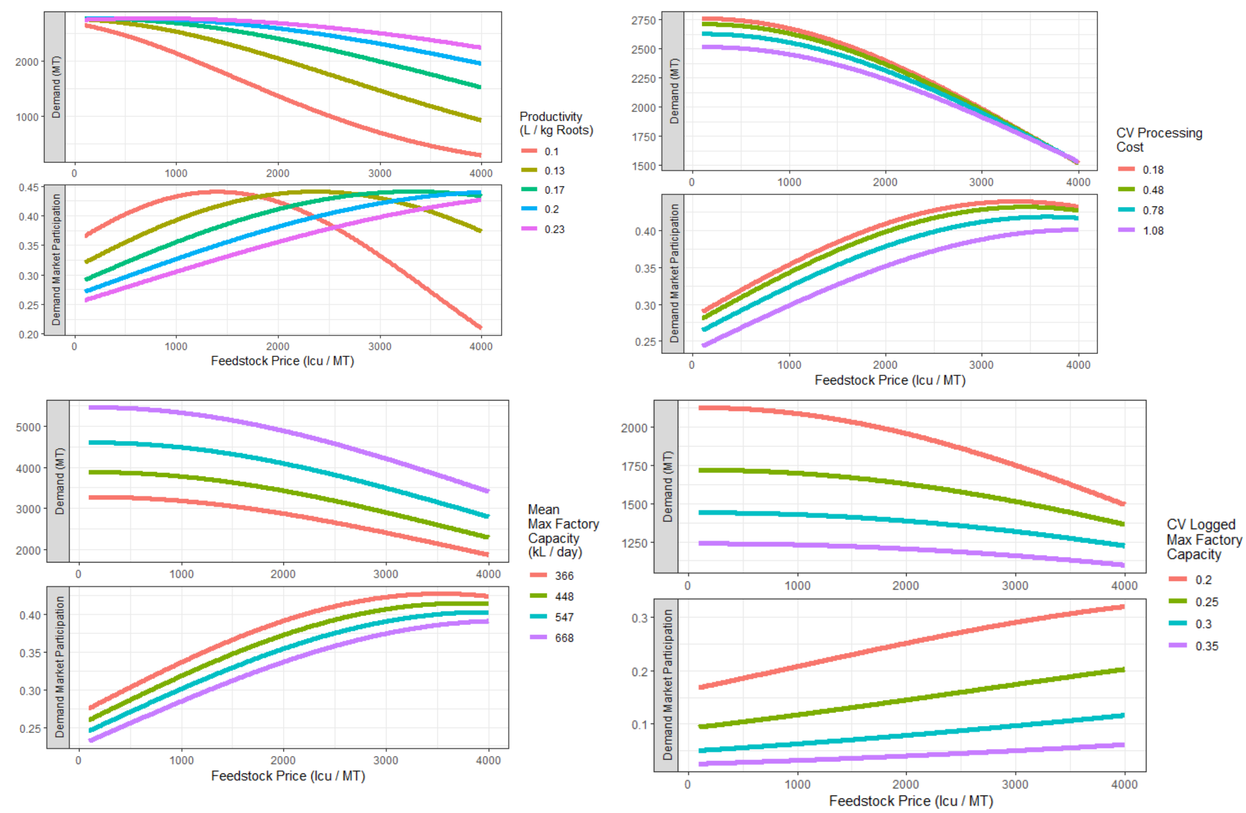


Figure 26: Demand and factory market participation curve sensitivity to changes in key parameters

On the demand side is also of interest to look at the influence of changes in the output price (Figure 27).

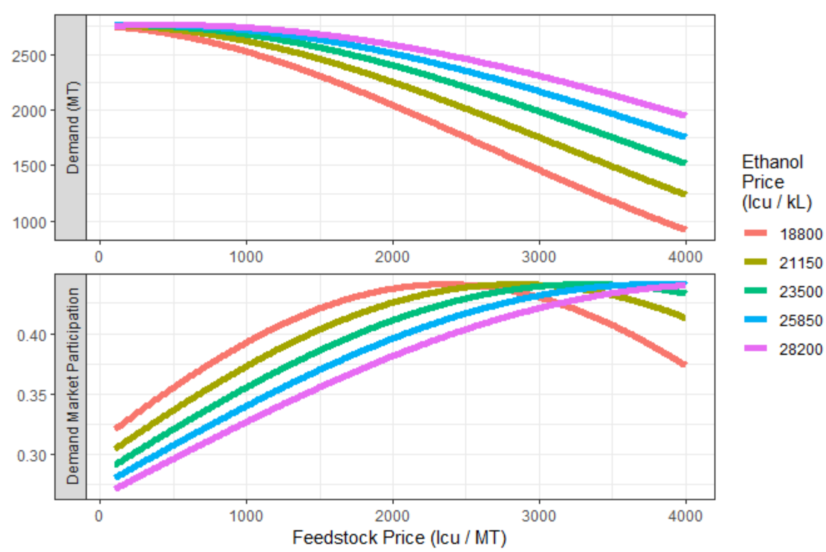


Figure 27: Demand and factory participation curve sensitivity to change in output price

- See the DEPEMap Documentation for full details.

F. Maps disaggregated by technology

Farm and factory market participation maps, disaggregated by technology, are given in Figure 28.

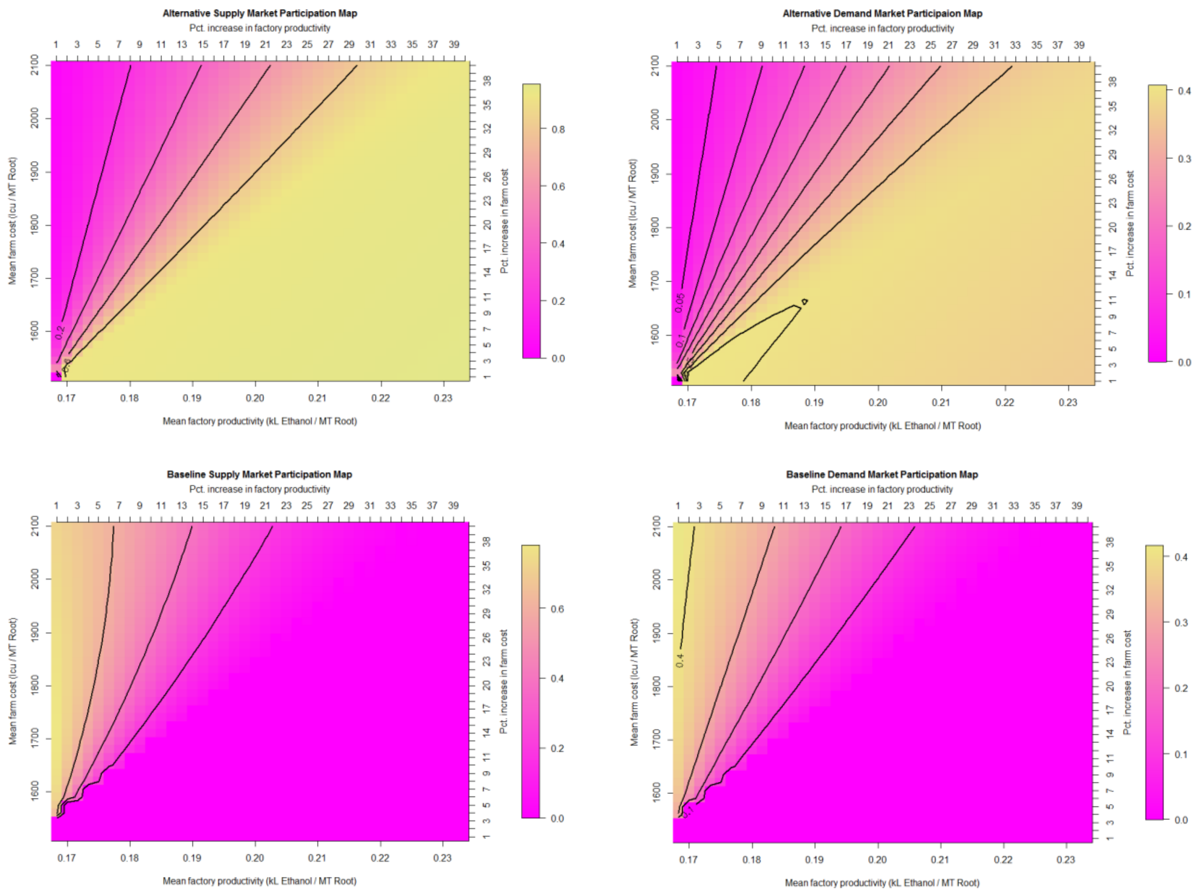
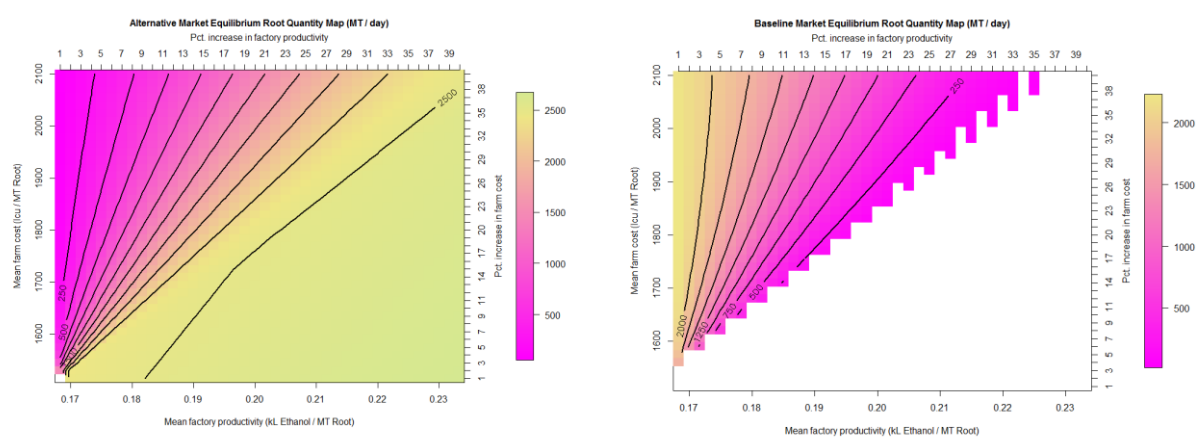


Figure 28: (Top rows) Farm and factory market participation maps disaggregated by technology. (Bottom row) Root output maps disaggregated by technology.

Root and ethanol output maps, disaggregated by technology, are given in Figure 29.



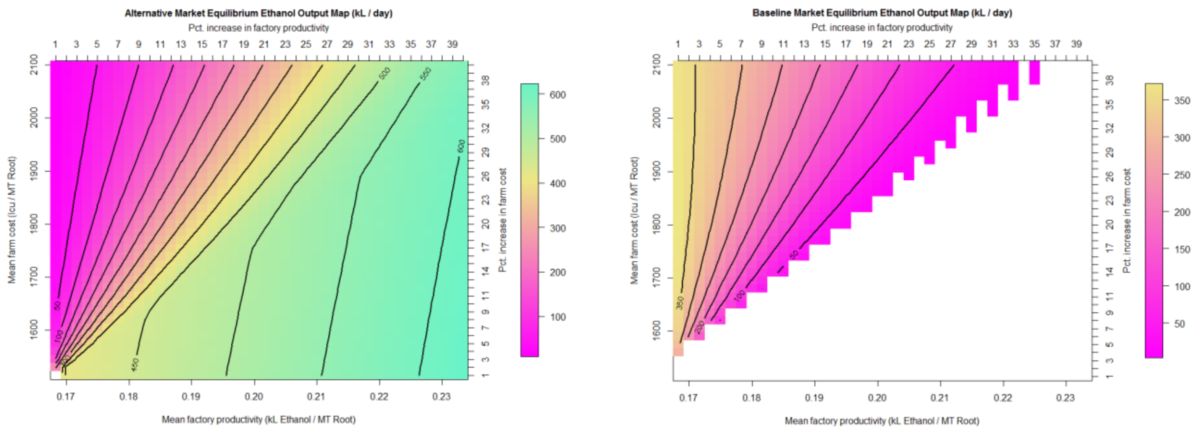


Figure 29: Root and ethanol output maps disaggregated by technology