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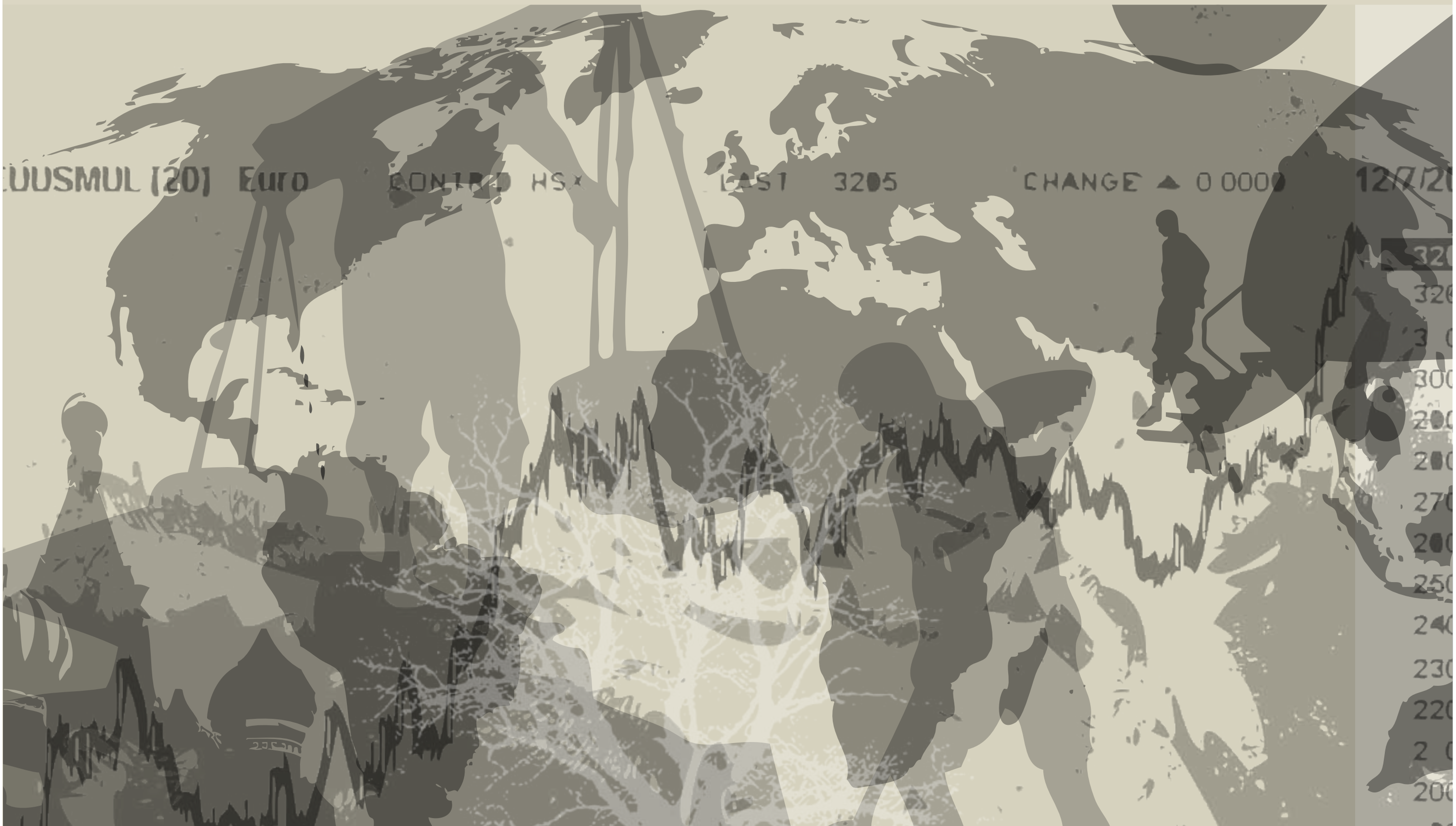

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Abstract

Potatoes are an important crop for food security in Bihar, providing significant income generating activities for participating farmers and an additional source of diet diversification for consumers. Recent reforms to the Agriculture Production Market Committee (APMC) Act and improvements in state-wide governance have provided further incentives for investment in the potato sector, particularly in cold storage facilities that can mitigate seasonal price fluctuations and improve the availability of potatoes. At the same time, climate change could have severe ramifications on the potato sector in Bihar, with some forecasts predicting a decline in yields of over 20 percent in the coming decades. In this paper, we look at the quantitative impacts over time of different investment, trade, and policy scenarios in the potato value chain, particularly those that can mitigate climate change effects, using a system dynamics model of the potato value chain that builds on previous qualitative studies (e.g. Minten et al. 2011). Preliminary results highlight that reducing storage costs, either through subsidies or increased competition, could reduce the price variability inherent with climatic shocks. On the other hand, encouraging conventional types of cold storage could have additional feedback effects that exacerbate climatic shocks, suggesting a need to consider "climate-smart" investments.

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1. Introduction

Climate change poses important risks to food security in India, particularly in areas that rely heavily on rain-fed agriculture. IPCC (2007) predicts a reduction in crop production of between 10-40% in India by 2100 in the absence of adjustments made in response to climatic shocks. The state of Bihar is especially vulnerable to climatic shocks, with average maximum daily temperatures predicted to increase between 4 and 7 degrees Celsius by 2080, with little changes in rainfall (Abdul Haris et al. 2015). These climatic shocks are poised to undo many of the positive gains made in the agricultural sector in the state since 2000 in terms of improved political governance and stability, enhancements in the business environment, and strong government support to the agricultural sector (Minten et al. 2011).

A potential mitigation strategy in the event of climate change is the development of modern value chains. These link farmers with high-value markets and can provide both greater opportunities in the variety of market outlets with which to sell (and to be employed) and improvements in marketing, distribution, and technology that can increase productivity and reduce losses, lowering the margins between farmers and consumers, and enhancing food security. Indeed, in the Indian context, Bihar has been a leader in market-based reforms with its repeal of the APMC Act that allows farmers to make direct linkages with buyers, without the need to rely on regulated markets (*mandis*) that add costs and reduce the efficiency of the marketing chain. An important area of inquiry is whether specific value chains for agricultural products can benefit stakeholders in the event of climate shocks, and the mechanisms by which this could arise.

In this paper, we provide a case study of the potato sector in Bihar and the potential that improvements to the value chain could have as a mitigation strategy against climate change. The paper builds upon earlier work by Minten et al. (2011), who characterized the value chain, and particularly the emerging role of cold storage facilities, in an in-depth study of two potato producing districts in Bihar based on primary survey data. Our study adds value to this previous analysis by operationalizing the characteristics of the potato value chain described in Minten et al. (2011), Shankar et al. (2014), and Singh (2011) into a quantitative system dynamics model in which policy simulations can be conducted (Rich et al. 2011). In this manner, we can highlight the impacts of alternative scenarios of climatic events overlaid with different policy interventions to assess their potential effects on food security. We pay particular attention to the levels and variability of prices and distributional benefits associated with different scenarios.

At the same time, while our model provides important insights on the potential ramifications of different scenarios, an additional contribution of our analysis is to infuse a systems thinking perspective to the issue of food security and sustainability more generally, highlighting in particular the interconnectedness between various components of the food system (Sonnino et al. 2014). To this end, we also consider qualitatively some of the additional aspects of the potato value chain that may generate different feedback effects that could counteract some of policy levers employed by government. This provides an additional perspective on some of the challenges associated with climate change, identifying key factors to take into account in designing mitigation options.

2. An overview of the potato value chain in Bihar

Potatoes are an important food crop in Bihar, ranking fourth in statewide production behind rice, wheat, and maize (Shankar et al. 2014). In 2010-11, Bihar accounted for about 15% of India's potato production, although this share of national production has fallen from 19% in 2007-2008 (Market Intelligence System 2012; Minten et al. 2011). As noted in table 1, production has been steadily increasing over the past decade, with the most recent statistics from 2013/2014 reporting production of over 6.5 million tons (compared to 5.7 million tons in 2005/2006). Most of this increase in production is due to enhanced productivity, as the area devoted to potatoes has erratically grown by just over 3 percent between 2005/2006 and 2013/2014 (table 1). Singh and Rai (2011) estimate that about five percent of arable land is devoted to potato production. Bihar is largely self-sufficient in potatoes, relying mainly on domestically-sourced sales of fresh potatoes to local markets with limited export of locally produced potatoes outside the state and almost no indigenous processing of potatoes (less than 1% of the state's crop is processed) (Shankar et al. 2014).

Table 1: Production of potatoes in Bihar, 2005/06-2013/14

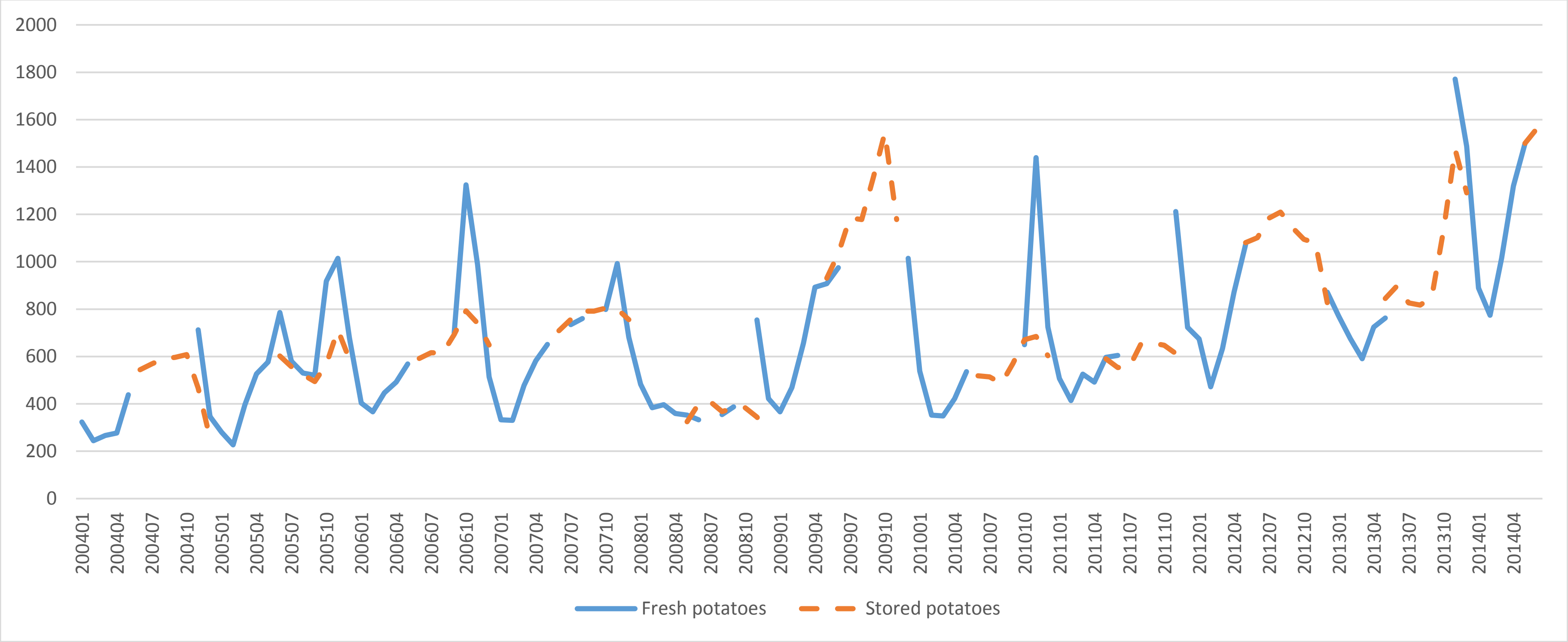
Crop year	Area ('000 ha)	Production ('000 tons)	Yield (tons/ha)
2005/2006	308.9	5702.5	18.46
2006/2007	322.8	5741.3	17.79
2007/2008	315.5	6019.7	19.08
2008/2009	310.3	5033.6	16.22
2009/2010	313.6	5387.2	17.18
2010/2011	314.0	5784.0	18.42
2011/2012	315.0	6102.0	19.37
2012/2013	323.0	6641.0	20.56
2013/2014	318.5	6536.0	20.52

Source: Horticulture Statistics Division, Department of Agriculture and Cooperation, http://nhb.gov.in/statistics/area-production-statistics.html

Potatoes are highly seasonal in nature. Planting takes place during October-March and crops take 80 to 90 days between planting and harvest, although this can vary by variety and time of planting, with early crops typically harvested between 60 and 70 days, and the main crop between

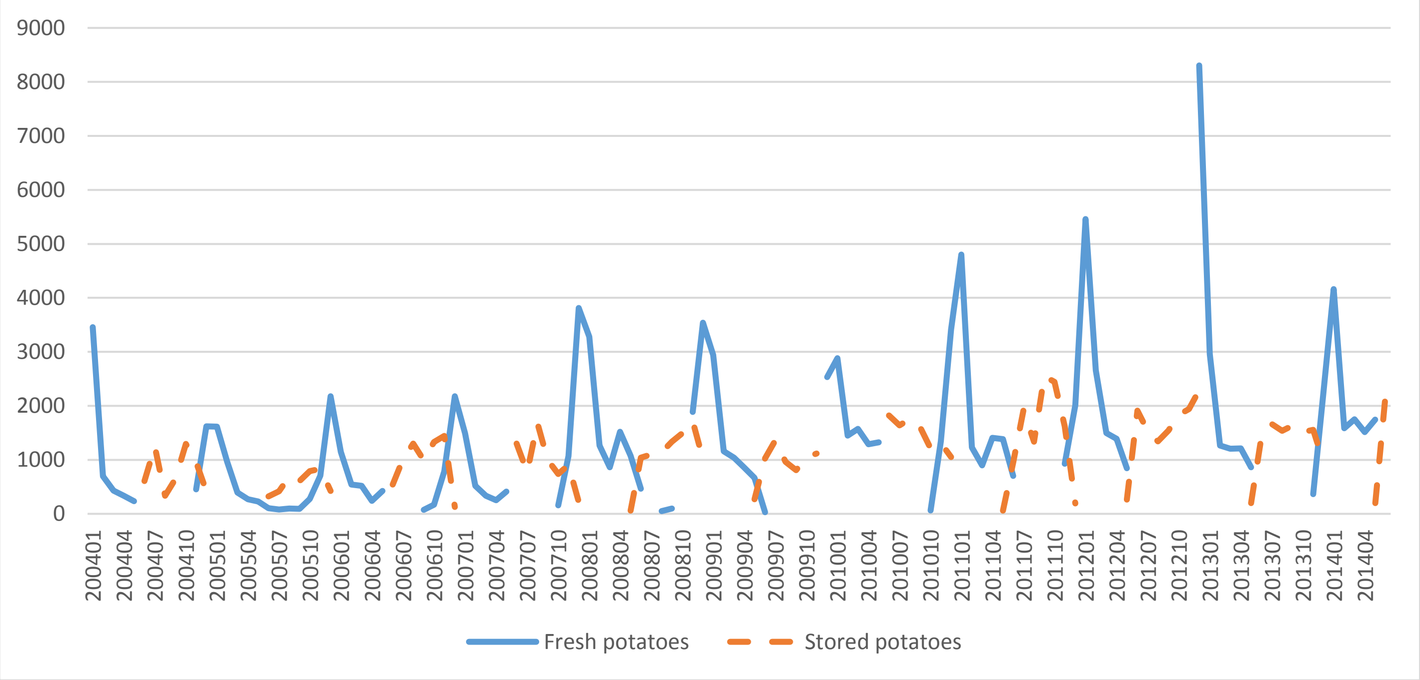
75 and 110 days (Singh and Rai 2011). This seasonality in production plays an important factor in significant price and sales fluctuations over the course of the year, as well as for an emerging role for cold storage systems to reduce these fluctuations and improve seasonal availability. Figures 1 and 2 illustrate the magnitude of price and volume fluctuations on a monthly basis between 2004 and 2014. After the main harvest period in the spring, prices of fresh potatoes steadily rise (and availability falls) until about May, after which there are significant sales from storage until the start of the next planting season in October (figures 1 and 2).

Figure 1. Potato prices (Rs/quintal) by month in Patna market by origin, 2004-2014



Source: Computed from Agricultural Marketing Board, Government of India

Figure 2. Potato arrivals (quintals) by month to Patna market by origin, 2004-2014



Source: Computed from Agricultural Marketing Board, Government of India

There has been a significant increase in the capacity of cold storage facilities in Bihar since 2000, driven by improved governance, provision of government subsidies to promote the horticulture sector, and improved technologies in facilities that reduce operational costs and in potato varieties that are more amenable to storage (Minten et al. 2011). The state-wide capacity for potato storage has increased from just under 700,000 tons in 2004 to nearly 1.04 million tons in 2013, based on government data. Minten et al. (2011) found that 92% of farm households in their sample in two districts in Bihar use storage at some point in the year. Despite this expansion, price variability remains high, with no clear trend over the past ten years (2004-2013, see table 2).

Table 2: Variability in potato prices in Bihar, 2004-2013

Year	Coefficient of variation of monthly prices
2004	34.56%
2005	27.46%
2006	23.19%
2007	27.49%
2008	13.66%
2009	35.68%
2010	20.31%
2011	13.05%
2012	25.90%
2013	29.26%

Source: Computed from statistics of the Agricultural Marketing Board, Government of India

Value chains for potatoes are relatively unorganized, although there is some coordination in transactions based on the services that buyers provide to farmers. Limited links exist between farmers and formal potato processors as in other Indian states for the production of value-added products (e.g., the presence of PepsiCo in states such as Punjab or West Bengal, see Pandit et al. 2014). Following the typology of governance forms of Gereffi et al. (2005), most transactions of potatoes follow a captive form of governance in which transactions between buyers and sellers are mediated by the provision of services (whether credit and/or storage) from the buyer to the seller, but where coordination of transactions does not depend on product attributes. As noted by Singh (2011), aggregators play an important role in providing credit to farmers and as such there are relational or captive forms of governance that bind farmers to buyers and obligate such transactions, although these ties are typically devoid of mandated specific characteristics or attributes of the potato crop itself. Intermediaries receive a significant portion of the final value of potatoes in the value chain. According to Singh (2011), farmers receive just 24% of value-added of potatoes in the peak season, and 18%

in the off-season, while intermediaries receive 50% and 57%, respectively. Farmers receive approximately 58% of the final consumer price (Singh 2011). Despite the lack of explicit coordination between buyers and sellers on potato quality attributes, there has been a shift in the varieties produced and sold by farmers. Traditional varieties of red potatoes, which fetch a price premium in the market, are being supplanted by white varieties, which have better storage characteristics and obtain higher yields (Minten et al. 2011). Sales downstream are largely conducted through market transactions based on price between wholesalers and retailers.

Bihar has been relatively progressive in its reforms of the APMC Act to allow direct sales to buyers and removing market fees. However, other charges from intermediaries still exist, which continue to raise transactions costs. Moreover, despite these reforms, traditional means of marketing persist, with farmers selling either to mandis, aggregators that serve as representatives for local mandis, cold storage facilities, or to collectors in the village that then sell to cold storage facilities (Minten et al., 2011; Singh 2011).

Potatoes play an important role in food security. Singh and Rai (2011) remark that potatoes provide more carbohydrates, protein, and dry matter per hectare than many important staple crops, including rice, wheat, and maize. In terms of protein per ha/day, potatoes provide three times the amount of rice, 2.5 times that of maize, and 20% more than wheat (Singh and Rai 2011). From a consumption standpoint, potatoes rank third behind rice and wheat in the monthly volumes consumed in Bihar, with just under 3.4 kg of potatoes consumed in both rural and urban areas (table 3). Potatoes represent just under five percent of the total monthly food budget and over a third of the budget allocated to vegetables in rural areas of Bihar, while in urban areas, potatoes comprise about four percent of the total monthly food budget and 29 percent of the budget on vegetables (table 3). Household data from Minten et al. (2011) showed that farmers are generally net sellers of potatoes, with about two-thirds of produced potatoes marketed for sale, and the remainder consumed on-farm or lost.[1]

Shankar et al. (2014) remark that from an income generation standpoint, potatoes are a particularly valuable crop, with yields 5 to 10 times more than other staple crops and which serve as important source of labor (approximately 79.5 million person days in Bihar, based on an average of 250 person-days labor required per hectare and 318,000 ha planted in 2013/2014). Further downstream, potato storage facilities also generate employment – an average of 11 permanent employees and

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[1] An examination of the household data set from Minten et al. (2011) revealed that of the 253 sampled farmers, only 65 made potato purchases. Moreover, only five farmers in the sample were deficit in potatoes (i.e. production less sales and own consumption was less than zero), but none of these farmers recorded any purchases of potatoes in the survey.

15 temporary employees work in each cold storage with a wage bill of Rs. 150,000 (USD 2,300) per year (Minten et al. 2011). Extrapolated over the 212 operational facilities in 2012, this implies over 5,500 people in permanent or temporary employment statewide and Rs. 825 million (USD 12.5 million) generated in value-added.

At the same time, potato production in Bihar is particularly vulnerable to weather-related phenomena that influences the variability of yield and which is magnified by the potential impacts associated with climate change. While yields have been steadily increasing over the past several years as reported in table 1, Saxena and Mathur (2013) note that the coefficient of variation of potato yields between 2000/2001 and 2010/11 was the highest in India at 36.3%. A couple of recent studies have modeled the impact of climate change on potato yields in the Indo-Gangetic plains in general and in Bihar in particular. Naresh Kumar et al. (2015) predict regional reductions in potato yields of 2.5% over 2010-2039, 6% over 2040-2069, and 11% over 2070-2099 based on current cropping patterns. However, they note that an important adaptation strategy for farmers is to vary the time of planting, which could increase yields by 6% over 2010-2039, while combining this with increased nitrogen and new varieties could increase yields by 10% over the same period and by 3% over 2070-2099 in spite of climate change. Abdul-Haris et al. (2015) report results from the InfoCrop model that are specific to Bihar that are much less favorable, with yield declines ranging between 3.3-5.9% by 2020, 12.5-15% by 2050, and 19.3-24.8% by 2080. Like Naresh Kumar et al. (2015), they find that delaying planting by ten days reduces these yield losses, but does not fully offset them.

Table 3. Per capita monthly consumption of selected food products in Bihar

Product category	Rural		Urban	
	Volume (kg/cap/mo)	Value (Rs/mo)	Volume (kg/cap/mo)	Value (Rs/mo)
Cereals				
PDS rice	1.321	8.77	0.582	4.04
Rice - other sources	4.723	87.5	4.784	99.16
Other rice products	0.228	5.38	0.227	5.39
PDS wheat/atta	0.983	5.35	0.414	2.38
Wheat/atta - other sources	4.601	56.12	5.098	70.52
Other cereals	0.278	5.46	0.203	5.24
Cereal: sub-total	*12.133*	*168.61*	*11.309*	*186.73*
Edible oils				
Mustard oil	0.508	43.66	0.562	47.21
Other oils	0.078	0.36	0.12	9.85
Edible oil: sub-total	*0.587*	*49.95*	*0.682*	*57.07*
Eggs and meat				
Eggs (no.)	1.003	4.17	1.213	5.34
Fish, prawn	0.239	22.08	0.187	18.68
Goat meat/mutton	0.05	10.86	0.058	13.04
Beef/ buffalo meat	0.024	2.29	0.035	2.68
Pork	0.003	0.44	0.001	0.11
Chicken	0.177	19.53	0.17	18.16
Other meat	0.001	0.04	0.001	0.08
Eggs, fish & meat: sub-total		*59.42*		*58.08*
Vegetables				
Potato	3.389	32.04	3.361	30.9
Onion	1.041	13.65	1.156	14.17
Tomato	0.253	3.75	0.39	6.33
Brinjal	0.654	8.61	0.514	7.49
Palak/other	0.626	5.27	0.522	4.91
Other vegetables	3.329	35.62	3.953	43.52
Vegetables: sub-total		*98.94*		*107.33*
Other food categories				
Cereal substitutes	0.026	0.41	0	0.01
Pulses: sub-total	0.744	35.46	0.822	41.68
Milk & milk products: sub-total		92.78		110.3
Salt & sugar: sub-total	0.758	19.1	0.783	20.72
Fruits, fresh: sub-total		20.38		32.39
Fruits, dry: sub-total	0.018	2.76	0.035	6.71
Spices: sub-total (grams)	349.155	39.42	352.123	41.38
Beverages: sub-total		22.93		27.83
Served processed food: sub-total		33.99		33.94
Packaged processed food: sub-total		23.49		36.93
Total: food group		667.64		761.11

Source: NSS data, 2012.

3. Methodology

3.1 Overview of system dynamics

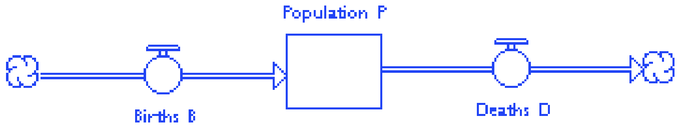
In this paper, we developed a system dynamics model of the potato value as a means of assessing the dynamic impacts of different policy scenario options. System dynamics (SD) is a simulation approach to modeling that highlights the dynamic interactions, delays, and feedbacks inherent in complex systems (Sterman 2000). From a technical standpoint, SD models are a collection of non-linear differential equations that are simulated (rather than solved numerically) over time to capture the evolution of dynamic phenomenon over time rather than to compute a particular equilibrium point. In biological systems, particularly agricultural and livestock markets that are characterized by biophysical delays and resultant cyclic behavior, SD models are a useful way to represent the overlays and feedbacks between biological phenomena with market behavior, and how different types of exogenous shocks to the system can influence system behavior over time (Rich et al. 2011). Moreover, because SD models are typically represented through a graphical modeling interface, they are accessible to a wider range of practitioners from various disciplines, thus allowing for multidisciplinary collaboration. An additional advantage of a SD modeling approach is to draw awareness about the complexity that exists within a multitude of systems, pointing out specific areas of feedback that could influence behavior over time. This type of systems thinking can provide powerful lessons even in the absence of formal quantitative modeling, as the qualitative maps initially developed to characterize the system can provide insights on their own (Sherwood 2002).

The main elements of SD models are stocks, flows, parameters, and feedback loops. Figures 3 and 4 provide illustrations of a simple stock-flow diagram of population growth with these elements included using the SD software iThink, version 10.6 (http://www.iseesystems.com). In figure 3, we show a skeleton stock and flow diagram that we build on further in figure 4. A stock (denoted in figure 3 as P, or population) simply reflects an accumulation of a good or service at any period of time, *t*. The quantity of goods or services in a stock at time *t* will depend on the rate of entry of goods or services into the stock (an inflow, B, denoting the birth rate) less the rate of goods or services exiting the stock (an outflow, D, denoting the death rate). Mathematically, this initial relationship can be (loosely) denoted as:

$$\frac{dP}{dt} = B - D \quad (1)$$

In an SD model, the diagram in figure 3 provides an analogous representation of equation (1). In other words, drawing the diagram found in figure 3 automatically codes the relationships between stocks and flows as a differential equation.

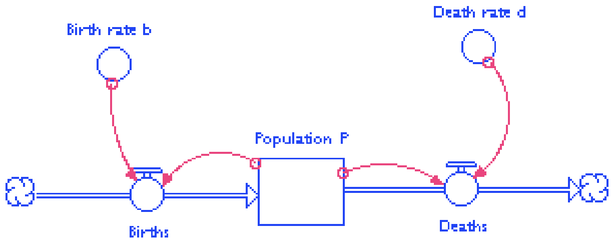
Figure 3. A simple representation of stocks and flows in system dynamics



Parameters in an SD model define the velocity by which inflows and outflows change over time as well as reflect a means of creating other parameters. In figure 4, we build on the previous figure by defining the fractional birth and death rates as parameters (circular shapes) that define the rate of change of our inflows and outflows. Within these two inflows, these parameters are multiplied by the stock of population to define the birth rate (fractional birth rate (b)* population) and the death rate (fractional death rate (d) * population). The thin red arrows that connect the parameters and stock to the inflow and outflow illustrate that a mathematical relationship exists between these parameters and the stock. Figure 4 can be more rigorously defined mathematically as:

$$\frac{dP}{dt} = bP - dP \quad (2)$$

Figure 4. A simple model of population in system dynamics



Feedback effects can be gleaned from figure 4 as well. As modeled, there are two feedback loops – one that defines the pattern of population growth from births and the other that defines the pattern of growth from deaths. The first of these feedback loops is what is termed a “reinforcing” loop i.e., it amplifies change in one direction (positive or negative). In this loop, as births increase, population increases, which means that in subsequent periods there are more births, leading to higher population levels, and so on. The second of these feedback loops is a “balancing” loop which counteracts change in the system. In this loop, as population increases, the number of deaths increases. This puts downward pressure on population in the next period, reducing the number of deaths, and eventually stabilizing population levels.

From the standpoint of modeling at the level of the value chain, SD models are particularly well-suited relative to other standard methods of economic analysis. Unlike partial equilibrium models that focus on the sector level (or multiple sectors), SD models of the value chain operate at a finer level of detail, capturing specific market interactions and, where data is available, the behavior of the value chain actors that exist between farmers and retailers (Dizyee et al. 2016a). They also have the potential of explicitly modeling institutional phenomena as an additional model overlay, including patterns of governance, market organization, and the adoption of new technologies. In this way, SD models reflect a platform for empirically assessing the impact of policy options identified in qualitative value chain assessments and providing guidelines on priorities for investment (Rich et al. 2011).

3.2 Model description

The model developed in this paper follows the commodity market model of Sterman (2000); see Cozzarin and Westgren (2000), McRoberts et al. (2013), and Dizyee et al. (2016b) for agricultural applications of this model. In this model, the production of a good or service is modeled along its distribution channel from inception to final sale, with parameters defined that govern demand relationships, production costs, and investment decisions determining price levels that affect how supply and demand change over time. The full model specification (graphical SD model as programmed in iThink) is given in Appendix A, while Appendix C provides model equations. Our model focuses on the production, storage, and retail side of the value chain, with other value chain actors such as collectors or processors not directly incorporated in this model (see Dizyee et al. (2016b) for an example of a value chain model with a fuller specification of value chain actors). However, as noted in the next section, we allow for simulations that take into account a simplistic specification of changes in value chain governance between farmers and intermediaries.

The Sterman (2000) model has been adapted to model the specific characteristics of potato production and marketing in Bihar. The model begins with the planting of potatoes (defined by the inflow “planting” in Appendix A) based on the area and yield of potatoes at a state-level and whether the time period in question is a planting month or not. As the model is simulated on a monthly basis, we only allow for planting during October-February to reflect the season in which potatoes are planted in Bihar. For other months of the year, this flow is turned off and set to zero. After planting, potatoes move to the stock “potatoes in the field” where planted potatoes in the model remain for a period of two months, after which they are harvested in the following month. This reflects the growing cycle of potatoes in Bihar that ranges between 60-110 days depending on variety and timing of the crop (Singh and Rai 2011).

We assume that planted area is fixed (based on data found in table 1), while yields depend on a combination of price effects (modeled as a simple double-log yield function of the expected price of potatoes and the price elasticity of yield). Stochastic events that influence yield patterns are included in our policy scenarios described in the next section. Ideally, we would parameterize yield effects to account for rainfall and temperature patterns, though we have not been able to do this at present.

After harvest, farmers have a choice as to where they can sell their marketable table (or ware) potatoes; we assume that a portion (40%) of potatoes are stored for seed, lost, processed, consumed on-farm, or exported which is not modeled further. We do not distinguish between varieties. Farmers can either sell table potatoes directly to the market, or they can utilize Bihar's bourgeoning cold storage facilities up to capacity limits that exist on their use. If they sell for storage, potatoes stay in storage for a period of six months. Following Wright and Williams (1991) and Fafchamps and Vargas-Hill (2005), a farmer will sell potatoes to storage if the expected price after storage minus storage costs are greater than the prevailing market price for fresh potatoes. While many neoclassical applications would assume rational expectations for price expectations, system dynamics models typically assume that actors are boundedly rational i.e., where decisions are bounded by the information available and cognitive limits of decision-makers (Simon 1957). In developing country contexts, where various livelihoods considerations influence decision-making and where information may be constrained by governance patterns present within value chains, an assumption of bounded rationality may be more appropriate. In our model, we assume that price expectations follow a first-order exponential smoothed process over a six-month period to reflect that price expectations follow a consideration of the previous season's potato prices sold from storage. We further assume that farmers receive 58% of the final retail price, based on Singh (2011). We alter this assumption later in our scenario analysis.

Potatoes that are either sold directly to the market or from storage contribute to the stock "market inventory" from which retail sales are made. Following standard principles from system dynamics models of supply and demand (Sterman 2000), changes in the actual levels of stocks available for inventory relative to desired levels drive changes in prices, which in turn affect demand and supply decisions. That is, the key decision for retailers concerns whether desired inventories are greater or lower than actual inventories. If desired inventories are less than actual levels, there will be movement to increase inventory levels which will bid up prices. Conversely, if desired inventories are greater than actual levels, there will be pressure to liquidate stocks, causing prices to fall. These price movements will influence demand, modeled as a simple double-log equation of potato demand as a function of own prices and income.

We simulate the model on a monthly basis for a period of 60 years. We chose this interval to highlight the evolution of the potato market over time intervals defined by previous climate change models. An important caveat in our analysis is that we do not fully consider changes in technology that could arise over the course the simulation period, as such information on technological shifts – and critically their rate of adoption by farmers – is largely unknown. Having said this, one could interpret our baseline scenario with no shocks as one in technological advances offset some of the predicted negative yield impacts associated with climate change. Important variables of interest include the evolution of prices and monthly sales, as well as their inter-seasonal variation. From the standpoint of food security, we posit that higher variation in prices could limit affordability among poorer consumer segments, and thus provides us a metric for assessing how different exogenous shocks and policy interventions could influence food security. We further computed a few welfare measurements that calculate the distributional impacts of different policies. We will discuss such scenarios in the next section.

3.3 Description of scenarios

An important component of our analysis highlights the potential impacts that climate change induced events could have on the potato value chain, and in turn how those impacts may influence food security. Accordingly, we are interested in understanding (1) what are the potential impacts that climate-related impacts might have on the value chain, particularly on prices, storage decisions, and producer and consumer welfare; and (2) given these impacts, how might alternative policies within the value chain serve to mitigate these effects?

We consider five types of scenarios in our model, and 11 different simulations in total, which are summarized in table 4. First, we run the baseline model alongside climatic reductions in yield as noted in Abdul-Haris et al. (2015) described in section 2 to generate three different climate change scenarios (scenarios 1-3). Second, based on the moderate yield reduction scenario (scenario 2), we look at the impacts of two different technical policy interventions implemented at the beginning of the simulation as a mitigation strategy. In particular, we examine a policy that subsidizes storage costs (scenario 4) and a policy that reduces postharvest losses (scenario 5). These policies on storage and postharvest losses represent policy levers that could improve availability and thus increase food security even if there are significant production shocks. Third, in scenario 6, we examine the impacts of a policy that stimulates intra-state trade to highlight improvements to domestic infrastructure and/or a reduction of trade barriers between states that often impedes trade. Fourth, in scenario 7, we look at improvements to the transactional governance of the potato value chain. In our model, improved governance, either through a reduction in transactions costs or the number of value chain intermediaries between farmers and consumers, or improved trust relationships would reduce the price gap between farm-gate and consumer prices. Accordingly, in these scenarios, we increase the proportion of the farm-gate price received by farmers to simulate the impacts of such measures. Further research following Dizyee et al. (2016b) would more fully explore these governance options, though empirical data on the types of relationships that exist among intermediaries in the potato value chain in Bihar are limited. Finally, scenarios 8-10 combine scenarios 4-6 with scenario 7 to examine the interactions of improved governance with different technical interventions.

We do not consider the impact of varietal changes or timing changes at the production side, due to a lack of sufficient data to parameterize climatic relationships on yield (although this is an area of interest for future research).

Table 4. Description of scenarios

Scenario number	Scenario description
0	*Baseline scenario* of the status quo (no climate shocks)
1	*Climate shock*: A low yield reduction case following Abdul-Haris et al. (2015), in which we consider a decline in potato yields of 4.5% starting in year 10 that continues for the duration of the 60-year simulation.
2	*Climate shock*: A moderate yield reduction case following Abdul-Haris et al. (2015), in which we consider a decline in potato yields of 4.5% starting in year 10 and a further decline in yields of 13.75% starting in year 30 for the duration of the 60-year simulation.
3	*Climate shock*: A high yield reduction case following Abdul-Haris et al. (2015), in which we consider a decline in potato yields of 4.5% starting in year 10, a decline in yields of 13.75% starting in year 30, and a further decline in yields of 22% starting in year 45 for the duration of the 60-year simulation.
4	*Moderate climate shock + storage subsidy*: In this scenario, we take the effects of scenario 2 as our baseline and look at the impact of a 50% reduction in storage costs (possibly from government subsidies or increased competition in facilities) from the onset of the simulation.
5	*Moderate climate shock + reduction in postharvest losses:* In this scenario, we take the effects of scenario 2 as our baseline and look at the impact of a 50% reduction in postharvest losses from the onset of the simulation.
6	*Moderate climate shock + increase in trade:* In this scenario, we take the effects of scenario 2 as our baseline and look at the impact of an increase of imports and exports from the state. To do this, we endogenize trade such that imports occur if demand exceeds market inventories, while exports arise if the opposite holds. We set the level of imports and exports at one-half the difference between inventories and demand. We assume that imports occur at Rs. 1/kg less than the autarky domestic price, and exports at Rs. 6/kg above. This is loosely based on price differentials in potato prices reported by Melchior (2016) – neighbouring states have prices approximately Rs 1/kg less than Bihar, while states with higher prices range from Rs. 1-13/kg.
7	*Moderate climate shock + improved value chain governance:* In this scenario, we take the effects of scenario 2 as our baseline and look at the impact of improved governance relationships, in the form of higher farm-gate prices for farmers. We assume that farmers receive 68% of the farm-gate price (up from 58% in the baseline) starting in year 10.
8	*Moderate climate shock + storage subsidy + improved governance*: This is a combination of scenarios 4 and 7
9	*Moderate climate shock + reduction in postharvest losses + improved governance*: This is a combination of scenarios 5 and 7
10	*Moderate climate shock + increases in trade + improved governance*: This is a combination of scenarios 6 and 7

From these shocks, we compute a number of metrics to assess the impact of different scenarios in the model. First, we compute the coefficient of variation (CV) of potato prices to track the variability and trend in prices to establish whether climate change and mitigation strategies influence the prevailing seasonality of price fluctuations. Second, we compute farmer welfare through an index of cumulative farm revenues over the simulation period. Third, we computed an index of consumer welfare based on estimates of consumer surplus. One of the challenges in using consumer surplus as a welfare measure when prices and incomes both change is the path dependence of the measure i.e., that the order in which these changes take place will provide different estimates of consumer surplus (Just, Hueth, and Schmitz 2004). A more accurate measure of consumer welfare is the use of compensating variation or equivalent variation, which measure consumer welfare based on (unobserved) Hicksian demand curves that alleviate the path dependence problem. Willig (1976) has shown that consumer surplus reasonably approximates compensating and equivalent variation where price and income changes are small. However, where price changes are large, as in this model where the simulation period takes place over 60 years, these errors in measurement are particularly compounded (Bacon 1995). Vartia (1983) proposed an algorithm to estimate compensating variation based on partitioning consumer surplus across multiple price changes to minimize the error associated with using consumer surplus for the entire price change. Accordingly, we followed this method to estimate compensating variation using computed consumer surplus to derive a more robust measure of consumer welfare.

3.4 Data sources

We summarize the key data and sources used in the model in table 5. We initialized the model on the cropping year 2011/2012 as this was the most recent year for most sources of parameters for the model. Production and price data come from the Department of Agriculture and Cooperation, as does information on storage. NSS data was used to compute consumption at a state level, based on per capita consumption data from the household survey and Census data on statewide population. Given the high rate of population and income growth in Bihar during the past decade, we decided to tamper down some of these assumptions from year 10 to reflect a more normalized growth process. From year 10, we assume that the annual population growth rate falls from 2.3% to 1% and the annual state GDP growth rate falls from 10.5% to 4%.

Elasticities were derived from a search of the literature and assumptions made by the authors. On the supply side, we assumed limited supply response from price changes, which given area constraints seems largely plausible. On the demand side, our data is based on a range of estimates. Most recently, Kumar et al. (2011) found price elasticities of vegetable demand of -0.515 and income elasticities of 0.259 on an all-

India basis. Anwar et al. (2015) computed demand elasticities of potatoes of -0.07 and -0.13 in Pakistan, while earlier work by Ahmed and Shams (1993) for Bangladesh found much higher elasticities of around -1.25. Fugile (1991) estimated demand elasticities of -0.5 to -0.8 for Tunisia during 1975-1990. Based on these range of figures, we assumed price elasticities of demand of -0.3 and income elasticities of demand of 0.3. To reflect the slower population and income growth process discussed earlier, we assume that the income elasticity of demand for potatoes falls to 0.1 in year 10 to reflect the increasing inferiority of potatoes as a consumption good over time. Sensitivity analysis of these parameters will be run in a later version of the paper.

Table 5. Key baseline data used in the system dynamics model

Parameter (units)	Value	Year	Source(s)
Area ('000 ha)	315	2011/12	Horticulture Statistics Division, Department of Agriculture and Cooperation, http://nhb.gov.in/statistics/area-production-statistics.html
Yield (tons/ha)	19.37	2011/12	Horticulture Statistics Division, Department of Agriculture and Cooperation, http://nhb.gov.in/statistics/area-production-statistics.html
Per capita consumption (kg/month/person)	3.375	2012	NSS 2012 data, averaged between rural and urban consumption
Population (million people)	104.1	2011	http://www.census2011.co.in/census/state/bihar.html
Annual population growth rate (%)	2.3	2001-2011	Computed from http://www.census2011.co.in/census/state/bihar.html, based on growth from 2001-2011. This is lowered to 1% from year 10.
Net production of potatoes (%)	60	2009	Minten et al. (2011) report 65% of potatoes marketed after losses, seed use, and home consumption; another 8-10% lost downstream
Annual growth in state GDP (%)	10.54	2005/06-2014/15	Ten-year average income growth rate in Bihar based on state-level statistics. This is lowered to 4% from year 10.
Storage capacity ('000 tons)	1030.4	2013	http://agmarknet.nic.in/binew.htm
Annual growth in storage capacity (%)	3.3		Computed from http://agmarknet.nic.in/binew.htm, annual growth 2009-2013
Price elasticity of area	0		Assumed based on limited growth in area
Price elasticity of yield	0.05		Assumed by the authors
Price elasticity of demand	-0.3		Assumed based on literature review (see text)
Income elasticity of demand	0.3		Assumed based on literature review (see text); this is lowered to 0.1 from year 10.
Baseline price (Rs/kg)	8	2012	Horticulture Statistics Division, Department of Agriculture and Cooperation

4. Preliminary results

We provide preliminary results from our simulations in tables 6 and 7, and in Appendix B which illustrates the evolution of price fluctuations over the 60-year simulation period. Table 6 provides a calculation of the coefficient of variation of potato prices over six 10-year periods to assess the change in price variability over time and how that is influenced by climatic events in our model and through different simulations. Table 7 provides indices of cumulative farm income and consumer surplus generated over the model simulation period in terms of deviations relative to the baseline and (where relevant) scenario 2.

Our baseline scenario shows steady rises in prices over the simulation period that are driven by growth in population and demand (see figures B-1 and B-3 with simulation 1). In the absence of trade, prices rise by more than four times over the sixty-year period, as supply cannot keep up with demand even without climate shocks. In the first set of simulations (scenarios 1-3), model results indicate an appreciably noticeable rise in prices relative to the baseline as yield shocks become increasingly severe over time (figures B-1 through B-3). From a variability perspective, we observe a reduction in price variability relative to the baseline despite the yield shocks (table 6). Increased yield shocks induce farmers to utilize storage facilities more frequently, buffering the fluctuation of prices but not mitigating their level. From a distributional perspective, farmers are slightly worse off from the more severe climate shocks in terms of cumulative farm income (table 7). Likewise, consumer welfare falls slightly in the low to moderate yield shock scenarios, partially but not fully buffered by higher income over the simulation. However, the most severe climate scenario reduces consumer welfare by 27% relative to the baseline (table 7).

In the second set of simulations (scenarios 4-5), we look at the two technical interventions associated with storage subsidies and reducing postharvest losses. Reducing storage costs has a moderating effect on price growth and markedly dampens price variability over time (table 6 and figure B-4). While this policy has little effect on production, it has a sizable impact on storage use which drives the reduction in both prices and variability. From a welfare perspective, relative to the moderate climate shock, farmers are slightly worse off under this scenario given the reduction in farm prices (table 7). Consumers, by contrast, are better off, with a nearly 5% rise in consumer surplus over the simulation period relative to the moderate climate shock that is driven by lower, less variable prices (table 7). By contrast, reducing postharvest losses in scenario 5 increases price variability for most of the simulation relative to the baseline and climate shock scenarios (table 6 and figure B-5). This is because while prices are lower on average in scenario 5 (figure B-5), this reduces incentives for storage, causing prices to fluctuate by more over time. From a welfare perspective, reducing postharvest losses is less beneficial for farmers than reducing storage costs, while the lower price levels induced by this policy is significantly more attractive for consumers, increasing consumer surplus by over 18% relative to the moderate climate shock (table 7).

Improved trade (scenario 6) sharply reduces prices and price variability through the greater availability of potatoes for sale at lean periods of the year (table 6 and figure B-6). This boosts consumer welfare by over 70% relative to the moderate climate shock scenario. By contrast, cumulative farm income falls by around 40% during the simulation period (table 7). This dynamic arises from the following. In initial simulation periods, both exports and imports occur during surplus and lean periods, respectively. As climate change impacts unfold over time, this combined with increased demand from steadily rising populations, reduces the available marketable surplus and thus restricts exports, causing either the lower autarky or import parity price to bind (depending on the season), lowering prices and thus incomes to farmers.

We should be cautious in interpreting our trade scenario results. Our approach does not capture general equilibrium effects or regional adjustments that would occur during a climate change scenario, and so likely overstates the negative impacts on farmers. Our results further highlight the positive impacts that trade has on price stability – in other autarky scenarios, farm gains come at the expense of high price variability from climate-induced supply shocks. The trade scenarios, by contrast, show important gains to consumers that significantly improves food security. Indeed, comparing these effects to the baseline highlights the important role that trade can play in minimizing the price distortions that climate change could exacerbate.

Reducing the gap between farm and consumer prices (scenario 7) has little impact on price levels and causes an initial increase in price variability that remains slightly above that of scenario 2 over the simulation period (table 6 and figure B-7). However, both consumers and producers benefit from this scenario, with cumulative farm income increasing by 17% relative to scenario 2, and consumer welfare increasing by nearly 1% (table 7). When improved governance is combined with the other interventions (scenarios 8-10), we find the greatest impacts in scenario 8 that combines reduced storage costs with better value chain governance. This simulation increases cumulative farm income by 12% and consumer surplus by nearly 5% (table 7). This highlights the importance of developing packages of policy interventions that achieve multiple aims, although this will come with a variety of transactions costs that are not considered in this analysis. This is an area for future research to uncover further.

Table 6. Coefficient of variation of potato prices over different simulation periods and scenarios

Months	*Scenario number:*										
	0	1	2	3	4	5	6	7	8	9	10
1-120	29.2%	29.2%	29.2%	29.2%	25.3%	34.2%	16.4%	30.8%	25.3%	34.0%	16.4%
121-240	22.4%	21.1%	21.1%	21.1%	15.8%	27.5%	14.7%	21.2%	16.2%	27.1%	14.8%
241-360	23.5%	23.7%	23.7%	23.7%	16.4%	31.0%	13.6%	23.6%	16.4%	30.7%	13.7%
361-480	23.4%	23.7%	19.7%	19.7%	16.5%	28.8%	11.9%	20.7%	16.6%	28.4%	12.0%
481-600	23.6%	23.6%	20.2%	20.2%	15.7%	26.4%	10.8%	20.3%	15.7%	27.0%	10.9%
601-720	23.5%	22.6%	19.2%	18.0%	15.4%	24.9%	9.9%	19.9%	15.4%	25.6%	9.9%

Source: Model results

Table 7. Welfare effects of different simulation periods and scenarios

Scenario	Cumulative farm income		Consumer surplus	
	Index 1	Index 2	Index 1	Index 2
Baseline	100	NA	100.0	NA
Scenario 1: Low climate shock	102.1	NA	107.0	NA
Scenario 2: Moderate climate shock	99.0	100	104.1	100
Scenario 3: High climate shock	98.8	NA	127.2	NA
Scenario 4: Moderate climate shock + storage subsidy	94.8	95.8	99.4	95.5
Scenario 5: Moderate climate shock + reduction in postharvest losses	94.3	95.3	85.1	81.7
Scenario 6: Moderate climate shock + increased trade	60.0	60.6	28.8	28.7
Scenario 7: Moderate climate shock + improved governance	116.5	117.7	103.2	99.2
Scenario 8: Combination, scenario 4+7	111.0	112.1	98.4	94.5
Scenario 9: Combination, scenario 5+7	111.0	112.2	86.1	82.7
Scenario 10: Combination, scenario 6+7	70.6	71.4	28.7	27.6

Source: Model results. Index 1 compares results to the baseline, while index 2 compares results to scenario 2 (moderate climate shock scenario). Note that consumer surplus results are read such that indices over 100 are *worse* for consumers (i.e., consumer surplus is more negative) compared to the baseline (or scenario 2), while indices less than 100 are *better* for consumers (i.e., consumer surplus is less negative). See text for details.

5. Discussion and conclusions

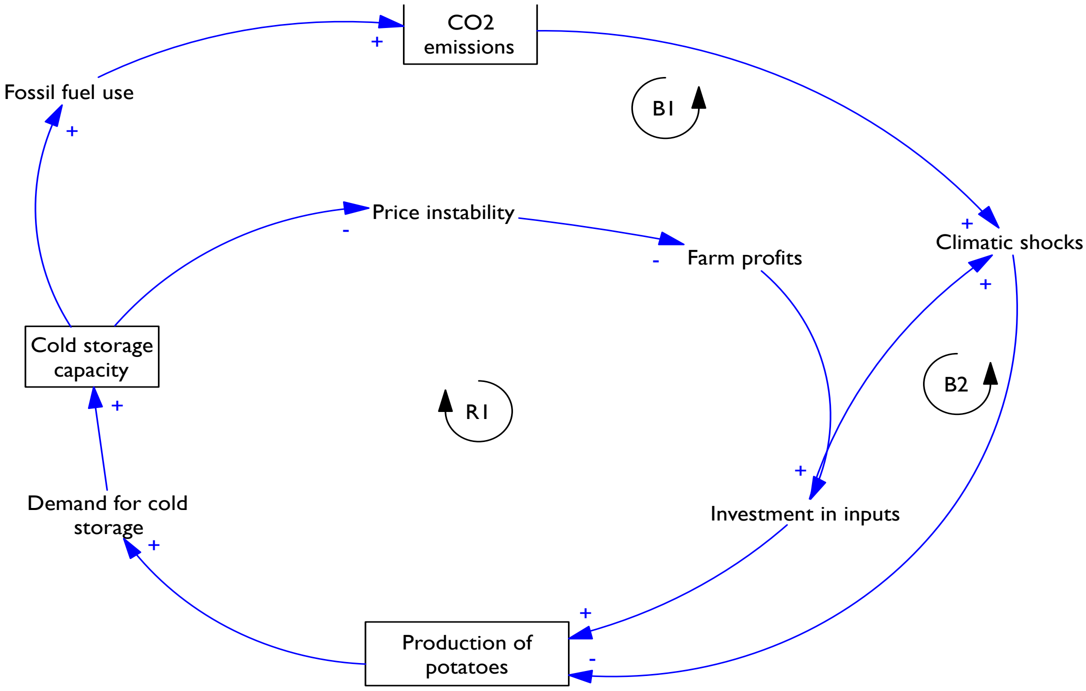
Our model results highlight a number of important insights. First, notwithstanding climate change (i.e., focusing on our baseline results), the combination of fixed area, slow yield growth, and high population growth will place pressure on potato availability in the future, increasing prices in the future, and potentially having important implications on food security for poorer consumer segments in the future. On the other hand, the expansion of cold storage, plays an important role in reducing price variability by providing producers with alternative venues to sell potatoes, although this in itself will not reduce prices for consumers.

Climatic shocks exacerbate these trends, causing larger spikes in prices over time. Sustained yield declines (as witnessed in scenarios 2 and 3) cause price variability to increase as well. Mitigation strategies that address climatic shocks such as reducing storage costs or postharvest losses reduce both the level and variability in prices, with the former strategy lowering price variability greater than the baseline. Improving governance alongside these policies could enhance the benefits for both consumers and producers. Alternatively, looking our shocks versus the baseline also highlights the role that technological improvements could have in mitigating climate impacts as well.

At the same time, encouraging the proliferation of cold storage could itself have unintended consequences that exacerbate climatic shocks, and a systems thinking perspective can help us identify these more clearly. Vermuelen et al. (2012) estimate that 396 megatons of CO_2 are generated from global systems from storage, packaging, and transport alone. James and James (2010) discuss the role that the cold chain for food products, including potatoes, has on climate change. They note that 15% of global electricity use is devoted to refrigeration, and remark that 1% of global CO_2 emissions and up to 3.5% of the greenhouse gas emissions of the United Kingdom are due to food refrigeration (both domestically produced and embedded in imported products). They also note the potential for huge savings in CO_2 emissions and energy use from potato storage in the UK, based on more efficient energy use and through technology transfer, estimating a reduction in CO_2 emissions of 30% per year and an annual decline in energy use (measured in GWh/year) of 60% (James and James 2010).

In figure 5, we illustrate these potential impacts through the use of a causal loop diagram (CLD) that highlights the feedback effects between different competing factors within the system. In the previous section, our quantitative model focused on the reinforcing loop (R1) that exists between enhancing cold storage capacity and production. An expansion of cold storage capacity is posited to reduce price instability, which raises profits (i.e., lower instability leads to higher profits), causing greater investment in inputs, higher production, and increased demand for storage in the future. However, as shown in figure 5, increasing the number of cold storage facilities could also lead to the imposition of a balancing loop (B1) that could act as a break on this virtuous cycle. B1 highlights that higher storage capacity will lead to greater fossil fuel use, raising CO_2 emissions, and enhancing climate shocks, which will place downward pressures on production. Furthermore, a second balancing loop, B2 predicts that greater investments in inputs themselves (such as in fossil fuel-based fertilizers) will also place stress on emissions, which will act as a further break on potato production.

Figure 5. Causal loop of the interactions between cold storage and climate change impacts



These feedback effects are an important part of the system though data constraints limit our ability to fully model their full impacts; modeling this following Bozorgi et al. (2014) who directly consider emissions functions within their cold chain model would be an interesting area of future research. Singh et al. (2014), in a study of potato cold storages in Madhya Pradesh, illustrate the variance in energy efficiency of existing facilities, and the potential that different interventions related to contracting for energy demand, energy efficiency, and building parameters associated with the orientation of the building and construction materials could have on saving both money and energy.

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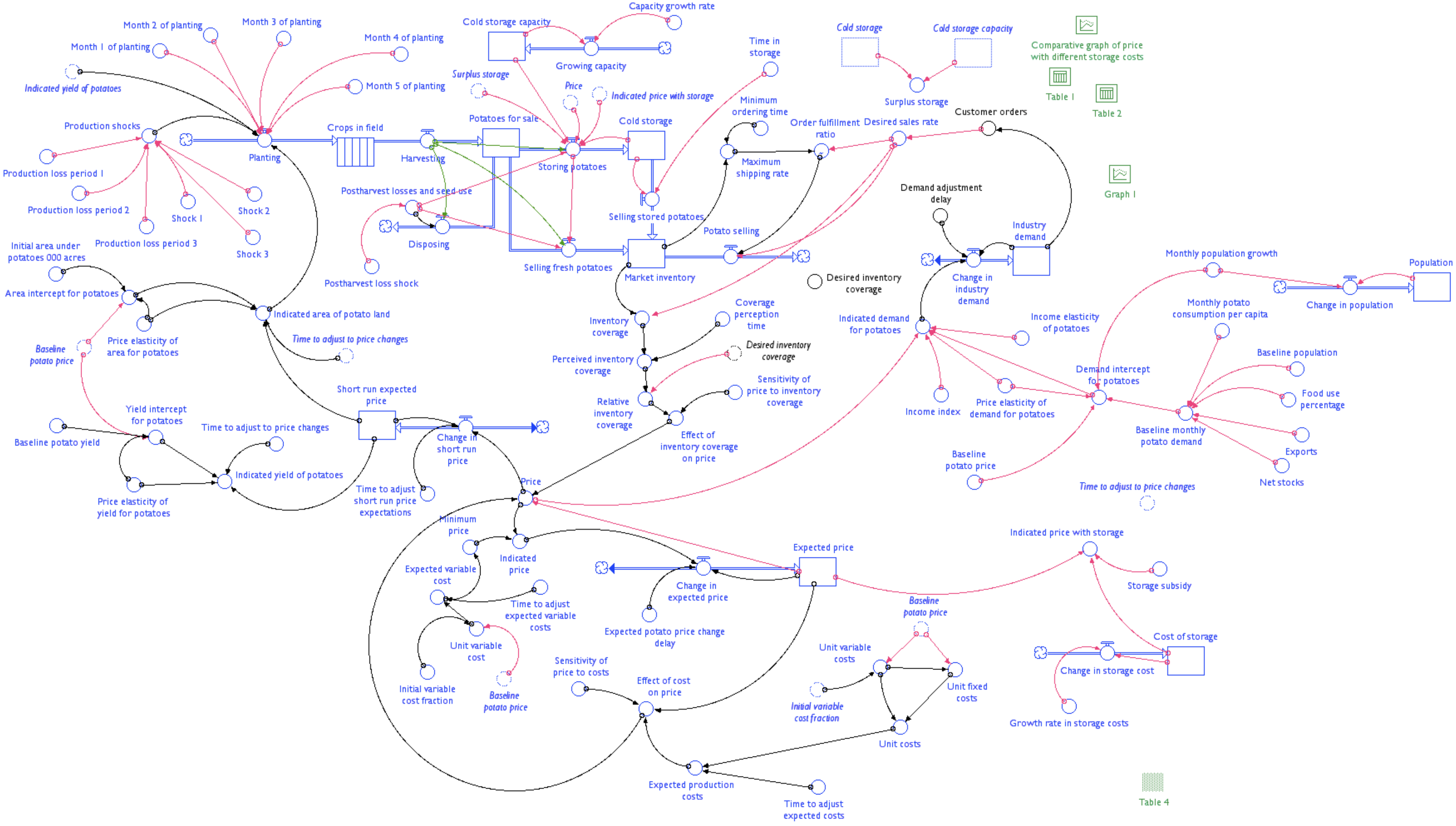
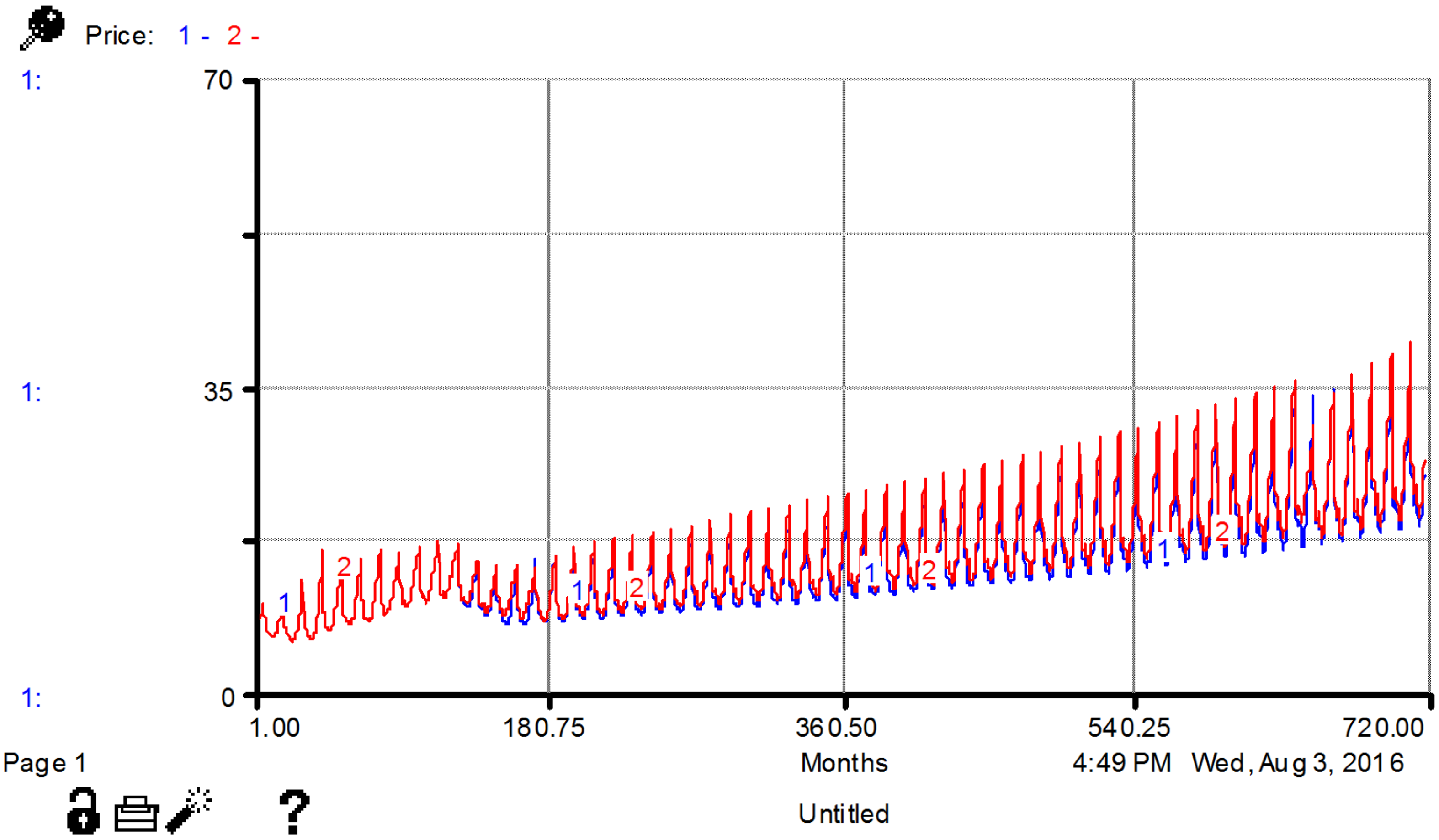
Appendix A. System dynamics model of the potato value chain in Bihar



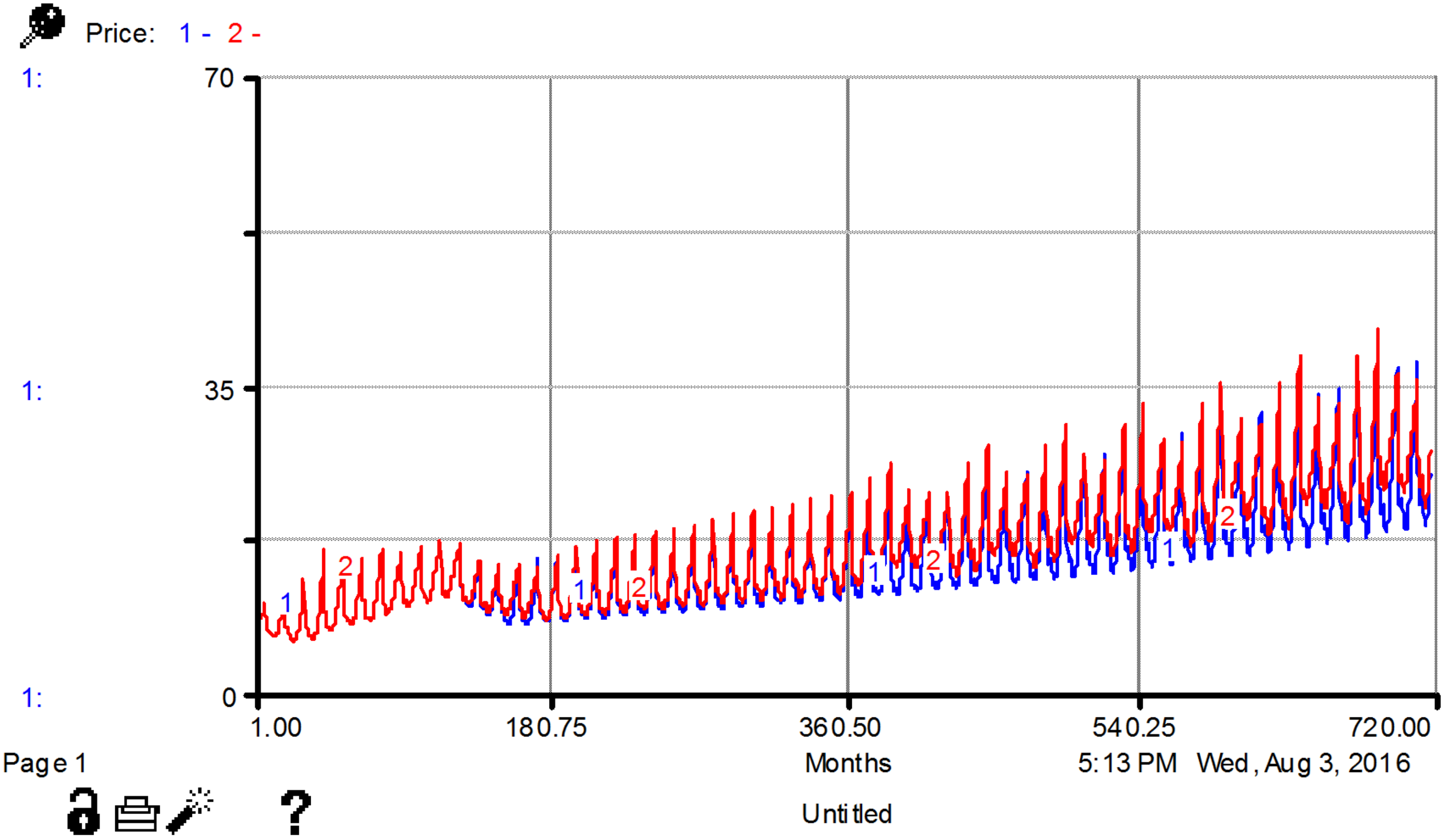
Appendix B: Results from simulations

Figure B-1. Evolution of potato prices in baseline and scenario 1



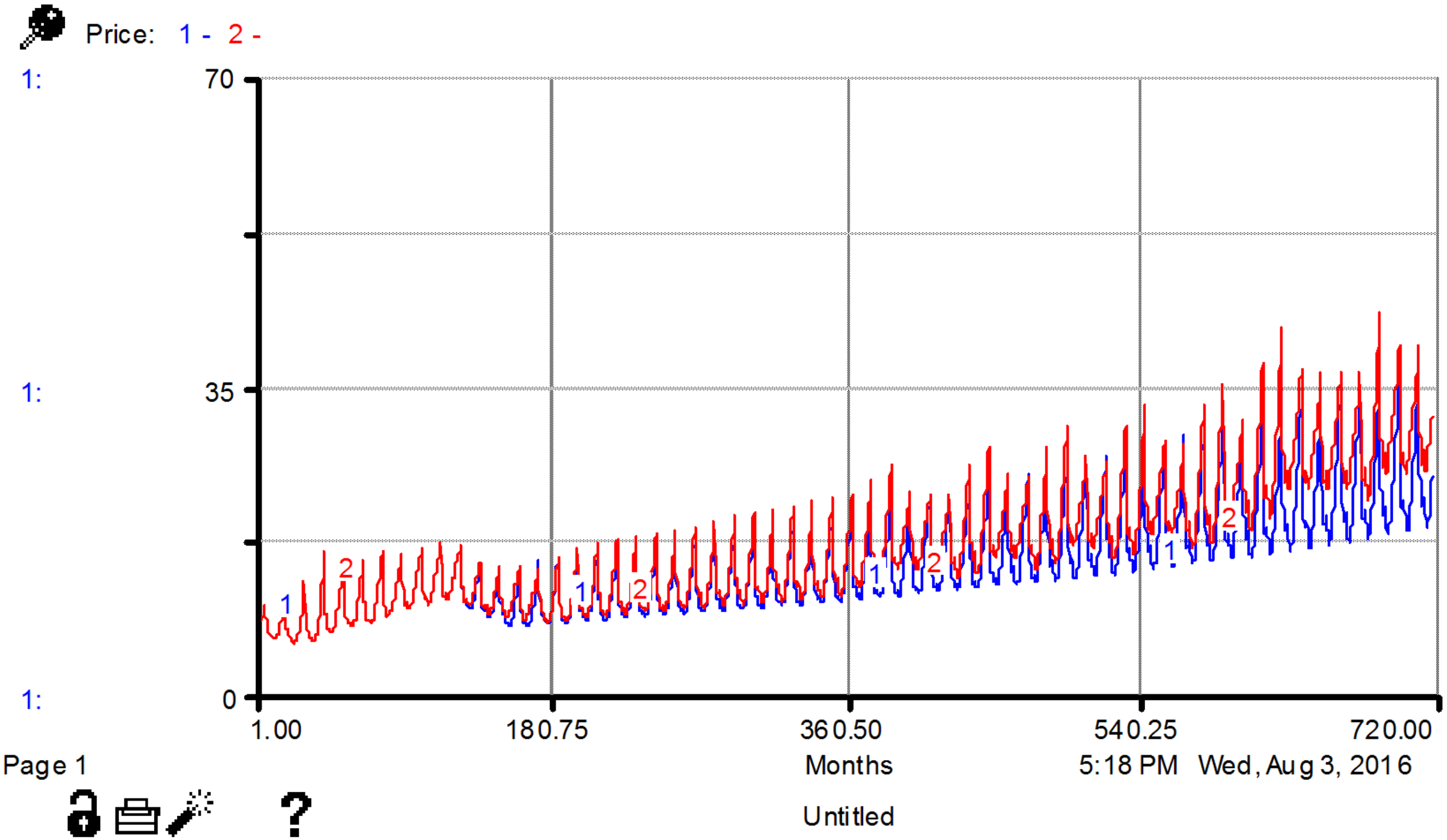
Source: Model simulations. Label 1 represents the baseline and label 2 represents scenario 1.

Figure B-2. Evolution of potato prices in scenario 2



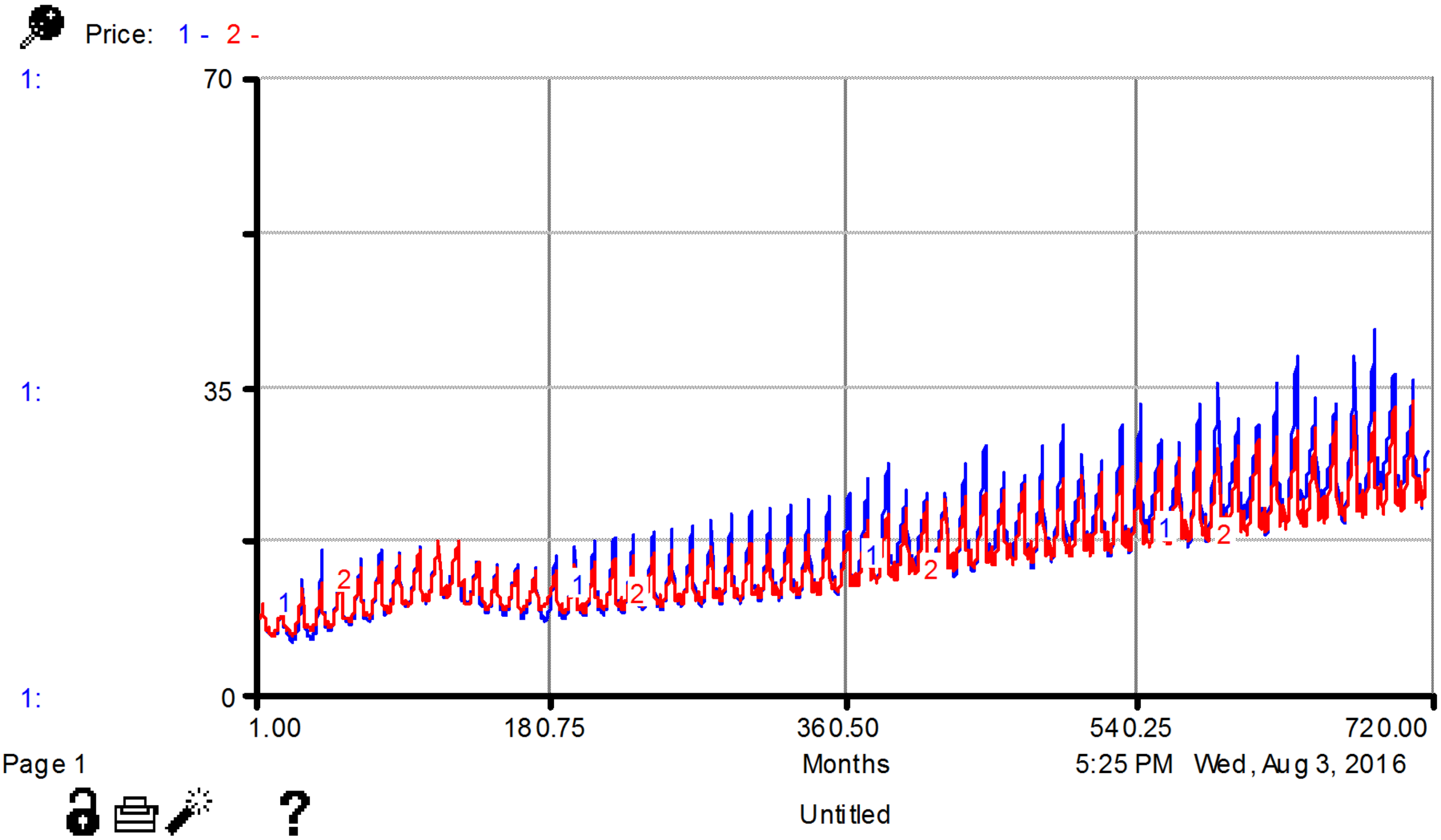
Source: Model simulations. Label 1 represents the baseline and label 2 represents scenario 2.

Figure B-3. Evolution of potato prices in scenario 3



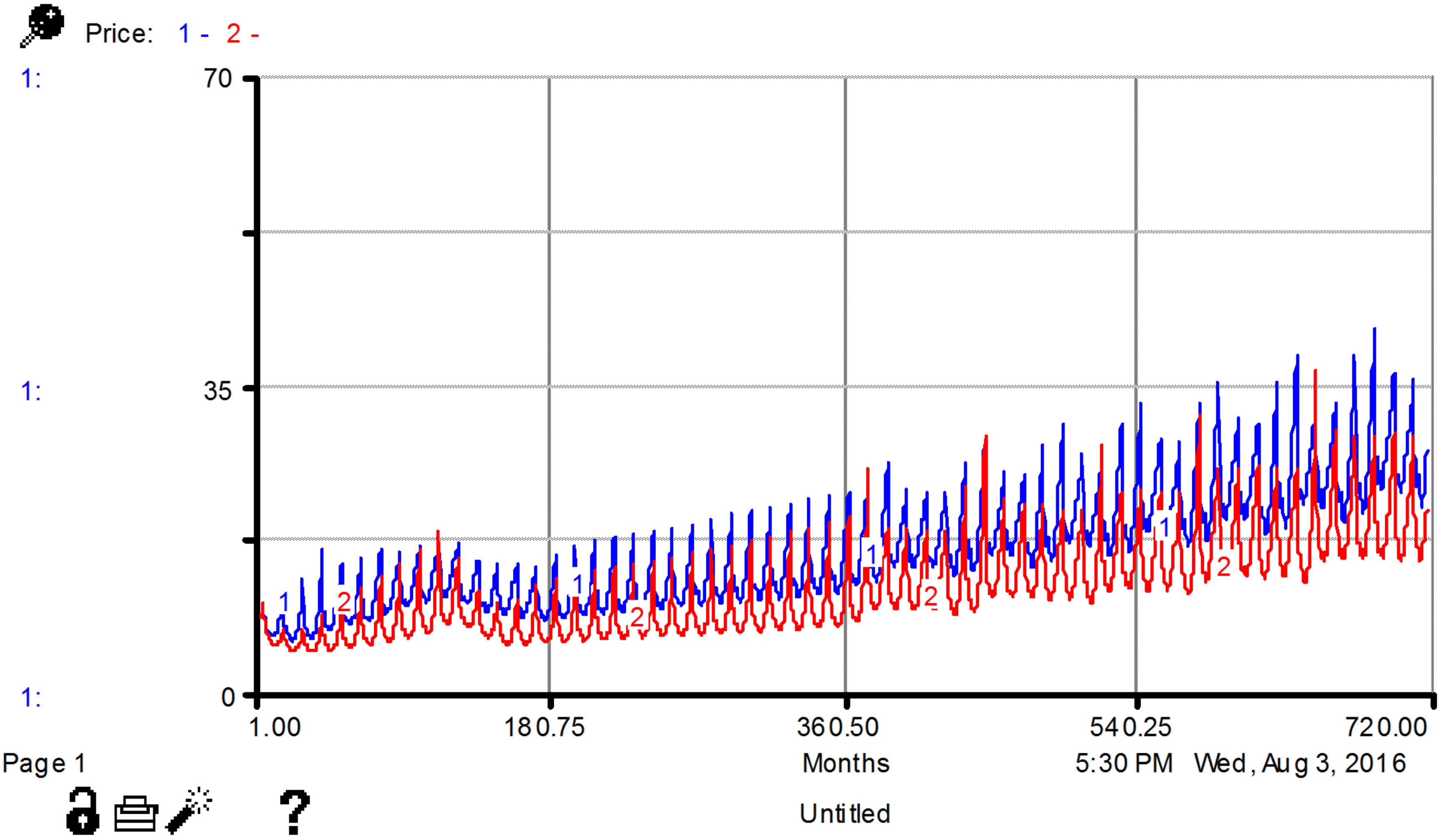
Source: Model simulations. Label 1 represents the baseline and label 2 represents scenario 3.

Figure B-4. Evolution of potato prices in scenario 4



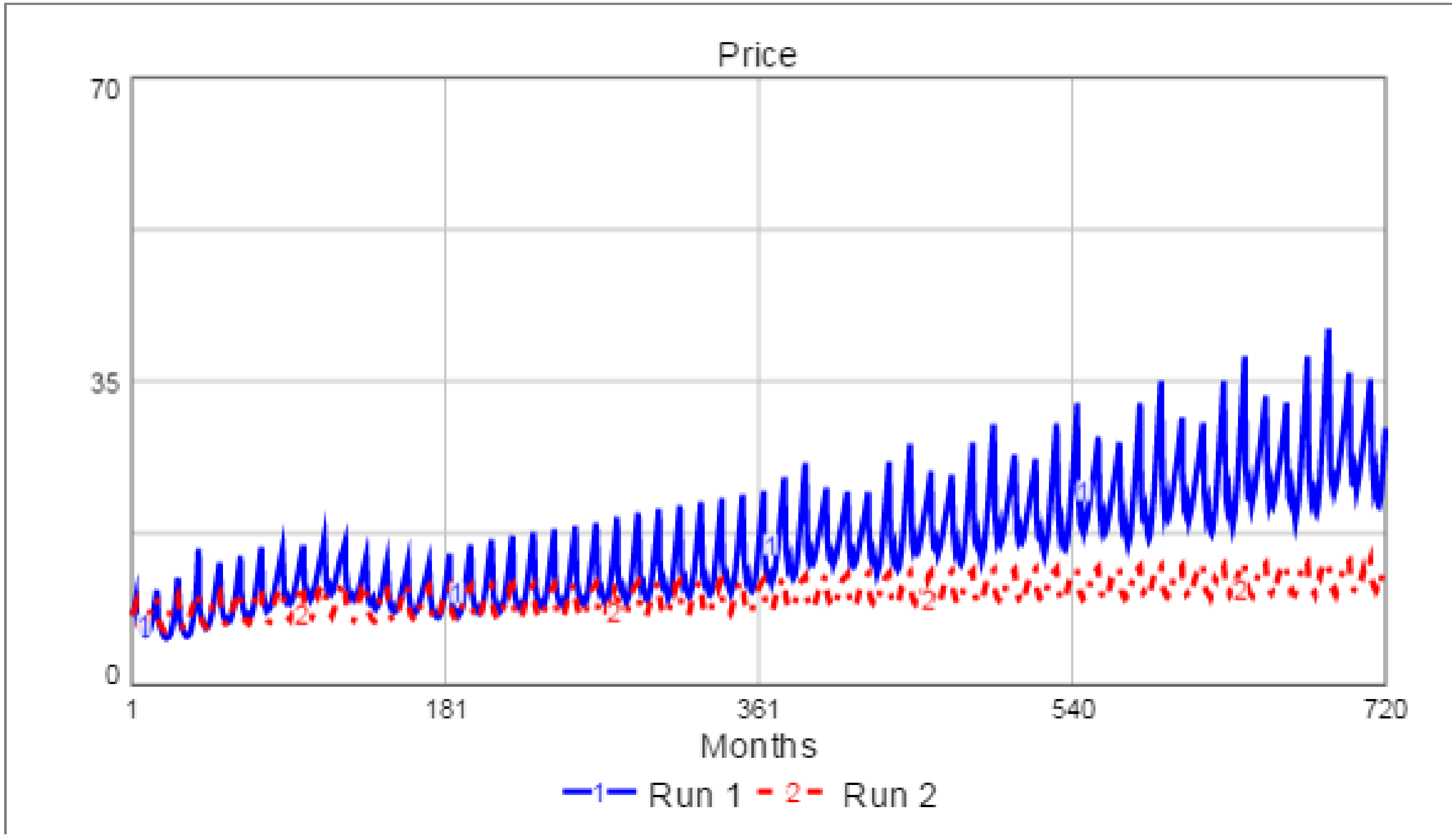
Source: Model simulations. Label 1 represents the baseline and label 2 represents scenario 4.

Figure B-5. Evolution of potato prices in scenario 5.



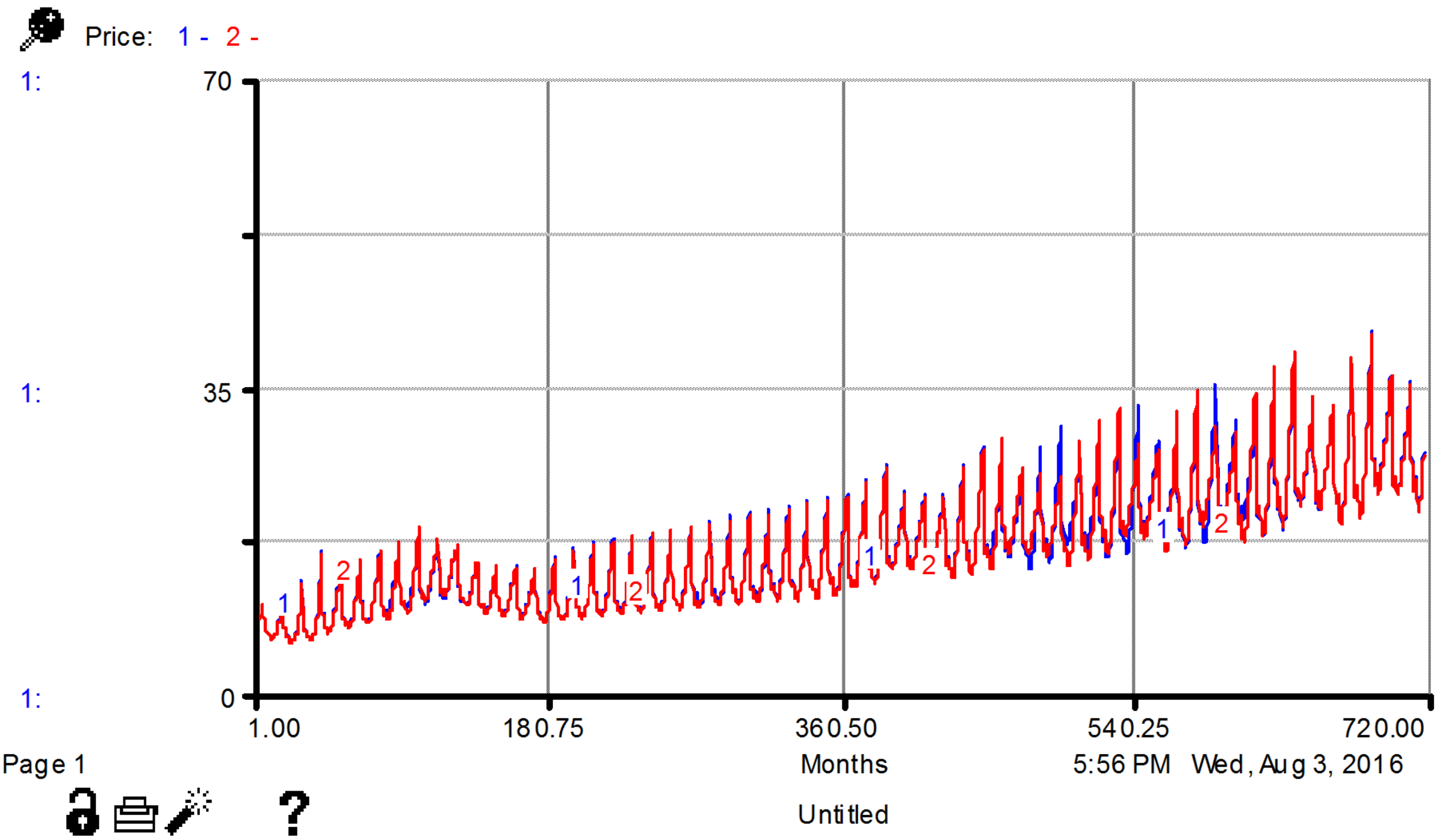
Source: Model simulations. Label 1 represents the baseline and label 2 represents scenario 5.

Figure B-6. Evolution of potato prices in scenario 6



Source: Model simulations. Label 1 represents the baseline and label 2 represents scenario 6.

Figure B-7. Evolution of potato prices in scenario 7



Source: Model simulations. Label 1 represents the baseline and label 2 represents scenario 7.

Appendix C. List of model equations from iThink

```
Expected_price(t) = Expected_price(t - dt) + (Change_in__expected_price) * dt
INIT Expected_price = Baseline__potato_price  {$/kg}
INFLOWS:
Change_in__expected_price = ((Indicated__Price-Expected_Price)/Expected_Potato_Price_Change_Delay)  {$/kg/week}
Industry__demand(t) = Industry__demand(t - dt) + (Change_in__industry__demand) * dt
INIT Industry__demand = Baseline_monthly__potato_demand  {kg/week}
INFLOWS:
Change_in__industry__demand = (Indicated_demand__for_potatoes-Industry__Demand)/Demand_Adjustment_Delay  {kg/week/week}
Cold_storage(t) = Cold_storage(t - dt) + (Storing_potatoes - Selling_stored_potatoes) * dt
INIT Cold_storage = 306
INFLOWS:
Storing_potatoes = if Price>Indicated_price_with_storage then 0 else if (Cold_storage<=Cold_storage_capacity) then min(Harvesting*(1-Postharvest_losses_and_seed_use), pulse(Surplus_storage,1,1)) else 0
OUTFLOWS:
Selling_stored_potatoes = Cold_storage/Time_in__storage
Cold_storage_capacity(t) = Cold_storage_capacity(t - dt) + (Growing_capacity) * dt
INIT Cold_storage_capacity = 904.7
INFLOWS:
Growing_capacity = Cold_storage_capacity*Capacity_growth_rate/12
Cost_of_storage(t) = Cost_of_storage(t - dt) + (Change_in_storage_cost) * dt
INIT Cost_of_storage = 1.5
```

INFLOWS:
Change_in_storage_cost = Cost_of_storage*Growth_rate_in_storage_costs
Cumulative_farm_income(t) = Cumulative_farm_income(t - dt) + (Change_in_farm_income) * dt
INIT Cumulative_farm_income = 0
INFLOWS:
Change_in_farm_income = Farm_income
Income(t) = Income(t - dt) + (Change_in_income) * dt
INIT Income = 1
INFLOWS:
Change_in_income = Monthly_income_growth*Income
Market_inventory(t) = Market_inventory(t - dt) + (Selling_fresh_potatoes + Selling_stored_potatoes + Imports - Potato_selling) * dt
INIT Market_inventory = Customer_orders*(Desired_Inventory_Coverage)
INFLOWS:
Selling_fresh_potatoes = Harvesting*(1-Postharvest_losses_and_seed_use)-Storing_potatoes
Selling_stored_potatoes = Cold_storage/Time_in__storage
Imports = if (Planting=0 and time›0) then pulse(Monthly_imported_volume,6,12)+pulse(Monthly_imported_volume,7,12)+pulse(Monthly_imported_volume,8,12)+pulse(Monthly_imported_volume,9,12)+pulse(Monthly_imported_volume,10,12)+pulse(Monthly_imported_volume,11,12)+pulse(Monthly_imported_volume,12,12) else 0
OUTFLOWS:
Potato_selling = Desired_sales_rate*Order_fulfillment__ratio
Population(t) = Population(t - dt) + (Change_in_population) * dt
INIT Population = Baseline_population
INFLOWS:
Change_in_population = Population*Monthly_population_growth
Potatoes_for_sale(t) = Potatoes_for_sale(t - dt) + (Harvesting - Selling_fresh_potatoes - Storing_potatoes - Disposing) * dt
INIT Potatoes_for_sale = 0

INFLOWS:
Harvesting = CONVEYOR OUTFLOW
OUTFLOWS:
Selling_fresh_potatoes = Harvesting*(1-Postharvest_losses_and_seed_use)-Storing_potatoes
Storing_potatoes = if Price›Indicated_price_with_storage then 0 else if (Cold_storage‹=Cold_storage_capacity) then min(Harvesting*(1-Postharvest_losses_and_seed_use), pulse(Surplus_storage,1,1)) else 0
Disposing = Postharvest_losses_and_seed_use*Harvesting
Short_run_expected_price(t) = Short_run_expected_price(t - dt) + (Change_in__short_run__price) * dt
INIT Short_run_expected_price = Baseline__potato_price {$/kg}
INFLOWS:
Change_in__short_run__price = (Price-Short_Run_Expected_Price)/Time_to_Adjust_Short_Run_Price_Expectations {$/kg/week}
Crops_in_field(t) = Crops_in_field(t - dt) + (Planting - Harvesting) * dt
INIT Crops_in_field = 0 {transit time an average of Singh and Rai; 60-70 days for early crop; 75-110 days for main}
TRANSIT TIME = 2
CAPACITY = INF
INFLOW LIMIT = INF
INFLOWS:
Planting = pulse(Indicated_area_of_potato_land*Indicated_yield_of_potatoes*(1-Production_shocks)/5*Month_1_of_planting,1,12)+pulse(Indicated_area_of_potato_land*Indicated_yield_of_potatoes*(1-Production_shocks)/5*Month_2_of_planting,2,12)+pulse(Indicated_area_of_potato_land*Indicated_yield_of_potatoes*(1-Production_shocks)*Month_3_of_planting/5,3,12)+pulse(Indicated_area_of_potato_land*Indicated_yield_of_potatoes*(1-Production_shocks)/5*Month_4_of_planting,4,12)+pulse(Indicated_area_of_potato_land*Indicated_yield_of_potatoes*(1-Production_shocks)/5*Month_5_of_planting,5,12)
OUTFLOWS:
Harvesting = CONVEYOR OUTFLOW
Area_intercept_for_potatoes = LN((Initial_area_under_potatoes_000_acres)/((Baseline__potato_price*Farmer_price_percentage)^Price_elasticity_of_area_for_potatoes))

Baseline_monthly__potato_demand = (Monthly_potato_consumption_per_capita*Baseline_population+Exports+Net_stocks)/1000*Food_use__percentage
Baseline_population = 104100 {000 people based on Census data}
Baseline_potato_yield = 19.37 {national statistics 2011-12 figure}
Baseline__potato_price = 8 {Rs/kg}
Capacity_growth_rate = 0.0527 {annual growth rate from Agmarket.nic.in}
Consumer_surplus_parameters = exp(Demand_intercept__for_potatoes)*(Income_index^Income_elasticity__of_potatoes)
Coverage__perception_time = 1 {months}
Customer_orders = Industry__Demand {kg/week}
Demand_adjustment_delay = 1 {month}
Demand_intercept__for_potatoes = LN((Baseline_monthly__potato_demand*((Population_index)))/(Baseline__potato_price^Price_elasticity_of_demand_for_potatoes))
Desired_inventory_coverage = 1 {months}
Desired_sales_rate = Customer_orders {kg/week}
Effect_of_cost__on_price = 1+Sensitivity_of_Price_to_Costs*((Expected_Production__Costs/Expected_Price)-1) {unitless}
Effect_of__inventory_coverage_on_price = Relative__Inventory__Coverage^Sensitivity_of__Price_to_inventory__Coverage {unitless}
Expected_potato_price_change_delay = 6 {months}
Expected_production__costs = SMTH1(Unit_Costs,Time_to_Adjust_Expected_Costs) {$/kg}
Expected_variable__cost = SMTH1(Unit_Variable_Cost,Time_to_Adjust_Expected_Variable_Costs) {$/kg}
Exports = 0
Farmer_percentage_shock = 0
Farmer_price_percentage = 0.58
Farm_income = Selling_fresh_potatoes*Price*(Farmer_price_percentage+Farmer_percentage_shock)+Storing_potatoes*Indicated_price_with_storage*(Farmer_price_percentage+Farmer_percentage_shock)
Food_use__percentage = 1
Growth_rate_in_storage_costs = pulse(0.02,24,12)

Income_elasticity__of_potatoes = if time <= 120 then 0.3 else 0.1
Income_index = Income
Indicated_area_of_potato_land = exp(Area_intercept_for_potatoes)*(smth1(Short_Run_Expected_Price*(Farmer_price_percentage+Farmer_percentage_shock),Time_to_adjust_to_price_changes))^Price_elasticity_of_area_for_potatoes
Indicated_demand__for_potatoes = exp(Demand_intercept__for_potatoes)*(Price^Price_elasticity_of_demand_for_potatoes)*(Income_index^Income_elasticity__of_potatoes)
Indicated_price_with_storage = Expected_price-(Cost_of_storage*(1-Storage_subsidy))
Indicated_yield_of_potatoes = exp(Yield_intercept__for_potatoes)*(smth1(Short_Run_Expected_Price*(Farmer_price_percentage+Farmer_percentage_shock),Time_to_adjust_to_price_changes))^Price_elasticity_of_yield_for_potatoes
Indicated__price = MAX(Minimum__Price,Price) {$/kg}
Initial_area_under_potatoes_000_acres = 315 {national statitics 2011-12}
Initial_variable_cost_fraction = 0.4 {unitless}
Inventory__coverage = Market_inventory/Desired_sales_rate {week}
Maximum__shipping_rate = Market_inventory/Minimum__ordering_time
Minimum__ordering_time = 1
Minimum__price = Expected_Variable__Cost {$/kg}
Monthly_imported_volume = 0*(1+Monthly_population_growth)^time
Monthly_income_growth = if time <=120 then .1052/12 else .04/12 {GSDP data Bihar, 2005/06-2014/15 for first 120 mos, assumes a reduction to 4% pa afterwards}
Monthly_population_growth = if time<=120 then 0.0243/12 else 0.01/12 {Singh and Rai 2011 cite 2.43 growth pa based on an initial pop of 83m. This is used for first 120 mos, then reduction to 1% assumed}
Monthly_potato_consumption_per_capita = 3.57
Month_1_of_planting = 1
Month_2_of_planting = 1
Month_3_of_planting = 1
Month_4_of_planting = 1

Month_5_of_planting = 1
Net_stocks = 0
Order_fulfillment__ratio = GRAPH(Maximum__shipping_rate/Desired_Sales_Rate {unitless})
(0.00, 0.00), (0.2, 0.2), (0.4, 0.4), (0.6, 0.58), (0.8, 0.73), (1.00, 0.85), (1.20, 0.93), (1.40, 0.97), (1.60, 0.99), (1.80, 1.00), (2.00, 1.00)
Perceived_inventory_coverage = SMTH1(Inventory__Coverage,Coverage__Perception_Time) {week}
Population_index = Population/Baseline_population
Postharvest_losses_and_seed_use = if time>1 then 0.4*Postharvest_loss_shock else 0.4
Postharvest_loss_shock = 1
Price = Expected_Price*Effect_of__Inventory_Coverage_on_Price*Effect_of_Cost__on_Price {$/kg}
Price_elasticity_of_area_for_potatoes = 0
Price_elasticity_of_demand_for_potatoes = -0.3
Price_elasticity_of_yield_for_potatoes = 0.05
Production_loss_period_1 = .046 {average of 3.3-5.9 decline in yield for 2020 from Abdul Haris et al 2015}
Production_loss_period_2 = .1375 {average of 12.5-15% yield loss by 2050 from Abdul Haris et al 2015}
Production_loss_period_3 = .2205 {average of 19.3-24.8% yield loss from Abdul Haris et al. 2015}
Production_shocks = if time>=120 and time<360 then Production_loss_period_1*Shock_1 else if time>=360 and time<600 then max(Production_loss_period_1*Shock_1,Production_loss_period_2*Shock_2) else if time>=600 then max(max(Production_loss_period_1*Shock_1,Production_loss_period_2*Shock_2),max(Production_loss_period_2*Shock_2,Production_loss_period_3*Shock_3)) else 0
Relative__inventory__coverage = Perceived_Inventory_Coverage/Desired_Inventory_Coverage {unitless}
Sensitivity_of_price_to_costs = 0.25 {unitless}
Sensitivity_of__price_to_inventory__coverage = -0.2 {unitless}
Shock_1 = 1
Shock_2 = 1
Shock_3 = 1
Storage_subsidy = 0
Surplus_storage = Cold_storage_capacity-Cold_storage

Time_in__storage = 6
Time_to_adjust_expected_costs = 12 {months}
Time_to_adjust_expected_variable_costs = 12 {months}
Time_to_adjust_short_run_price_expectations = 12 {months}
Time_to_adjust_to_price_changes = 12 {months}
Unit_costs = Unit_Variable_Costs+Unit_Fixed_Costs {$/unit}
Unit_fixed_costs = Baseline__potato_price-Unit_Variable_Costs {$/kg}
Unit_variable_cost = (Baseline__potato_price)*Initial_Variable_Cost_Fraction {$/kg}
Unit_variable_costs = Initial_Variable_Cost_Fraction*(Baseline__potato_price) {$/kg}
Yield_intercept__for_potatoes = ln(Baseline_potato_yield/((Baseline__potato_price*Farmer_price_percentage)^Price_elasticity_of_yield_for_potatoes))

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