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The Dynamics of Agricultural Commodities and Their Responses to Disruptions of Considerable Magnitude

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Abstract

An agricultural commodity production cycle model consisting of corn, beef, and dairy sectors was constructed for the purpose of exploring the propagating effects of large-scale disruptive events. In an initial proof-of-concept exercise, we considered an agricultural disruption scenario in which foot-and-mouth disease (FMD) is introduced into the U.S., causing a large-scale outbreak of the disease in both beef and dairy cattle. The magnitude of disruption to the beef and dairy sectors are presented under the existing FMD response policy and then improvements under two alternative policies are shown.

Introduction and Motivation

A project team consisting of participants from Argonne National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories has been tasked by the U.S. Department of Homeland Security with developing a risk-based decision support system that provides insights for making critical infrastructure protection decisions by considering all 14 critical infrastructures and their primary interdependencies. The purpose of this modeling effort is to simulate disruption scenarios, evaluate consequences, and evaluate the effectiveness of proposed mitigation actions.

In the initial 6-month, proof-of-concept phase, our goal was to demonstrate capabilities in building and linking SD models of multiple infrastructures to begin developing insight into infrastructures as dynamic systems. In this first phase we exercised the system of linked models using two disruption scenarios – one in telecommunications and one in agriculture. The telecommunications disruption scenario explored categorical complexity as the effects of a disruption telecommunications cascaded into other linked infrastructures such as electric power

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and banking and finance. The disruption in agriculture was more self-contained, with interesting dynamics generated by the structural complexity to be found in agricultural commodity production systems. The purpose of this paper is to describe the model of agricultural production that was developed and to present some interesting initial results.

Model description

This work builds on the seminal publication of Meadows (1970) on commodity production cycles (that is, the "hogs" model). The basic feedback structure for production cycles proposed by Meadows is shown in the CLD in Figure 1. Meadows showed that exogenous fluctuations propagate to cause oscillatory/cyclic behavior and that cycle periods from the model compared well with the durations of historical commodity cycles. The purpose of Meadows modeling effort was to develop a more powerful tool for the design of commodity stabilization policies.

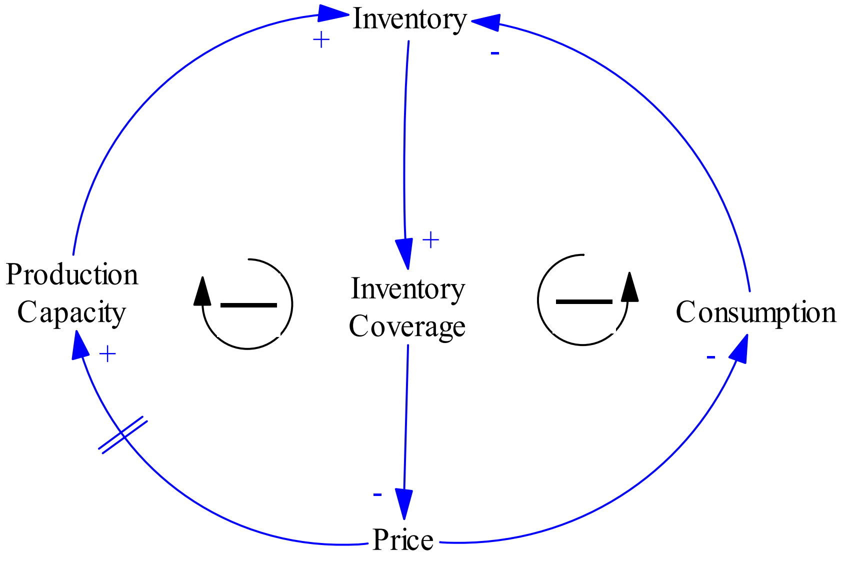
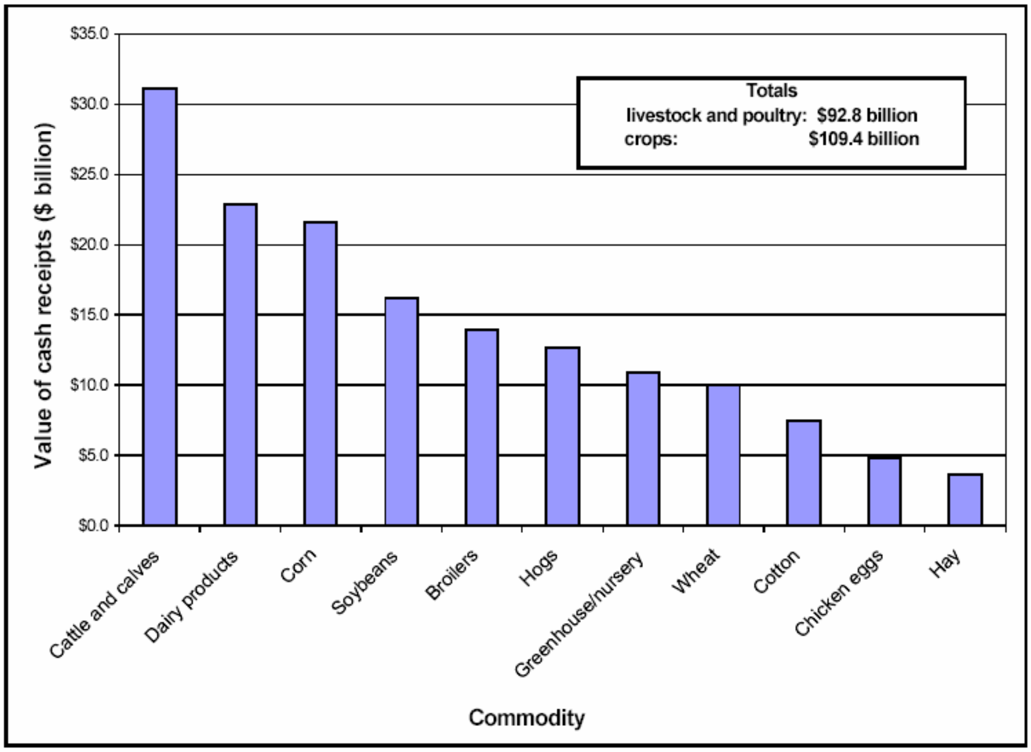


Figure 1. Feedback loop structure for commodity production cycles (after Meadows, 1970).

Our purpose for modeling agricultural commodity production is somewhat different. In our work for the Department of Homeland Security, we are tasked with understanding the propagating effects of large-scale disruptive events (whether they occur naturally or by malevolent attack). Comparing the relative magnitude of various disruptive events can help to guide investments for prevention. In building and analyzing SD models, we hope to develop insights about the robustness of existing systems to various disruptions. Given that an event occurs, we can evaluate various policies for how best to mitigate the disruption and facilitate restoration.

The initial incarnation of the agricultural commodities model simulates interacting agricultural commodities – corn, beef, and dairy. Together, these three sectors account for nearly 40% of cash receipts for agricultural products in the U.S. (see figure 2). Our intent is to eventually expand the model to include soybeans, broilers, and hogs. Animal feed is a very elastic market where the relative pricing of other feeds such as soymeal can have a great deal of impact on corn prices. On the demand side, hogs and broilers compete with cattle for animal feed. In addition, prices for alternative meats affect consumer demand for beef. Eventual inclusion of these six sectors will allow us to account for almost 60% of cash receipts for agricultural products in the U.S. (see again, figure 2).



Source: *Agriculture Fact Book 1998*, U.S. Department of Agriculture, Office of Communications, November 1998, pp. 43-44.

Figure 2. Values of the top 10 agricultural commodities, 1996.

Figure 3 illustrates how corn production interacts with beef production. In the U.S., almost 60% of corn production is used as animal feed. The CLD in Figure 4 shows the interactions between the three modeled agricultural sectors currently implemented in the U.S. agriculture commodities model. Here the price of corn affects beef and dairy production because added costs affect profit margins. Although hogs and broilers are not yet modeled explicitly, a simple elasticity is used to vary their consumption of feed as a function of the corn price. Similarly, corn exports are varied elastically as a function of corn price. (For readability exports were not shown in the figure.)

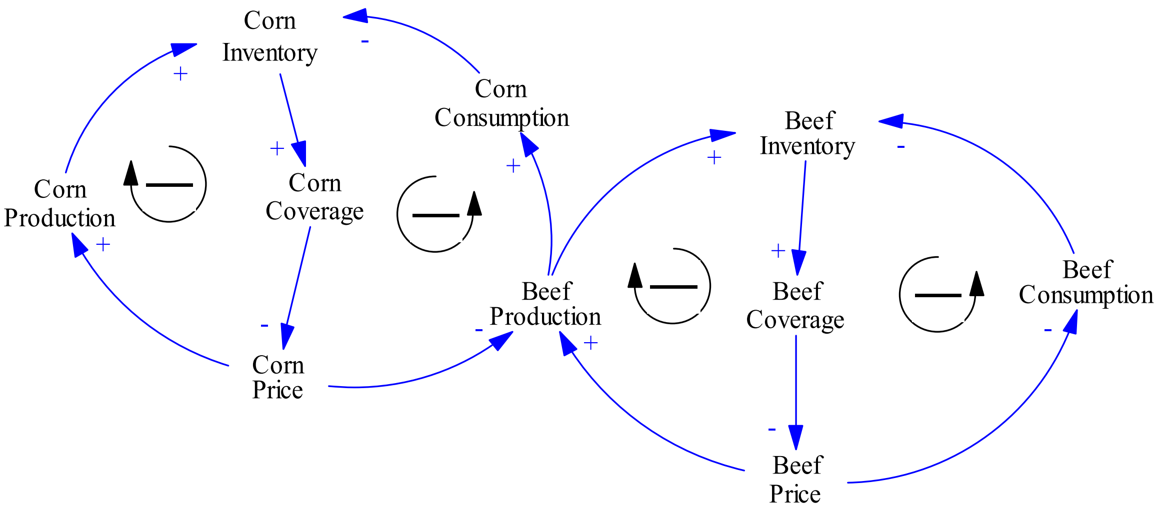


Figure 3. An example interaction between agricultural commodity production cycles.

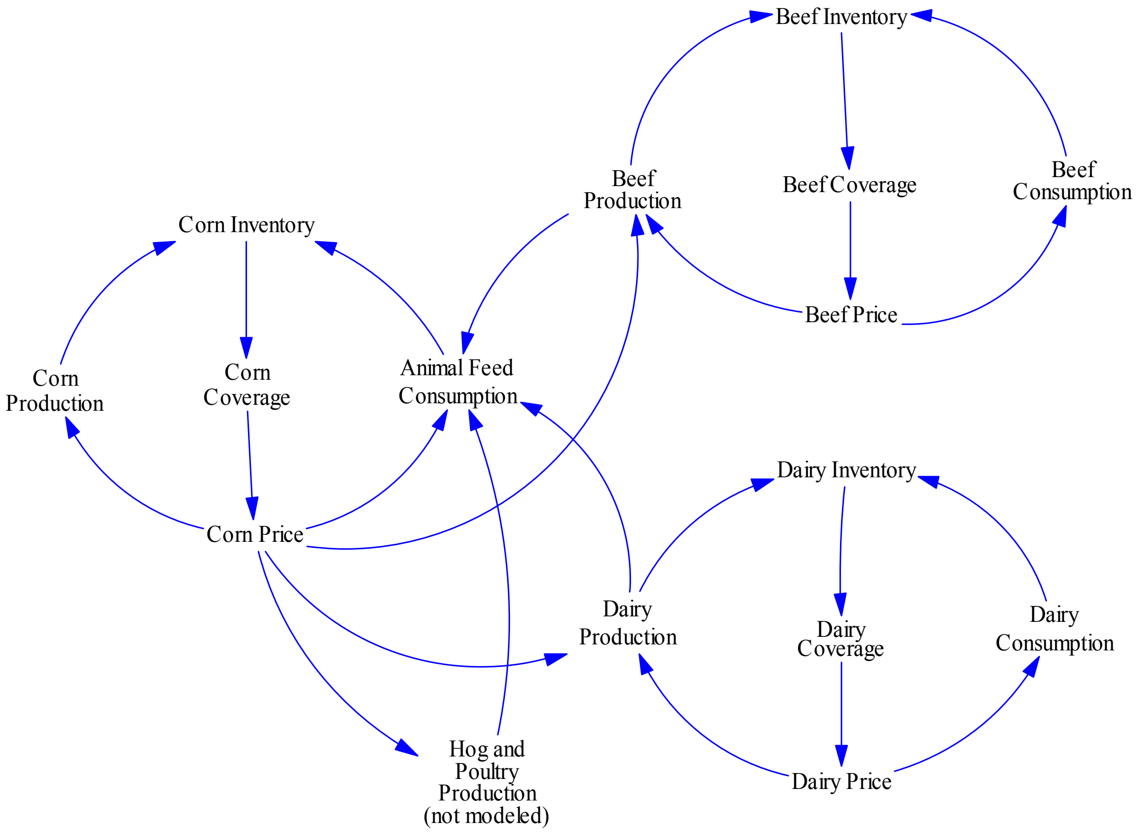


Figure 4. Interactions between the corn, beef, and dairy sectors in the U.S. agricultural commodities model.

Figure 5 shows the stock and flow diagram for the corn sector. The negative feedback loop for production is identified by the orange arrows. Since corn production is so strongly seasonal (planted in the spring and harvested in the fall), seasonal effects are explicitly captured in the model. Although in reality, farmers can respond to price signals during the growing season by varying their applications of fertilizer and pesticide, the foremost way they respond to price is in their decision about how much corn to plant in the spring. In the model this is the only way for corn producers to respond to price. Harvested corn accumulates in the fall and is depleted over the course of the year until the next harvest. Harvested corn is distributed three main ways. Of course, corn to be used as animal feed is of primary interest to us. The relatively high elasticity of this demand for corn is captured either explicitly in the beef and dairy sectors or implicitly using a simple elasticity for hogs and broilers. Initially in equilibrium, animal feed accounts for 58% of total demand. The demand for corn that goes to milling operations is inelastic relative to animal feed and is assumed constant for the purposes of this model. Milling operations process corn for food and industrial applications. Major products include ethanol, high fructose corn syrup and other sweeteners, starches, cereal, and alcohol. Milling operations account for 23% of demand. Exports account for 19% of demand. The feedback loop for consumption does not explicitly appear in this sector because it occurs by way of the beef and dairy sectors.

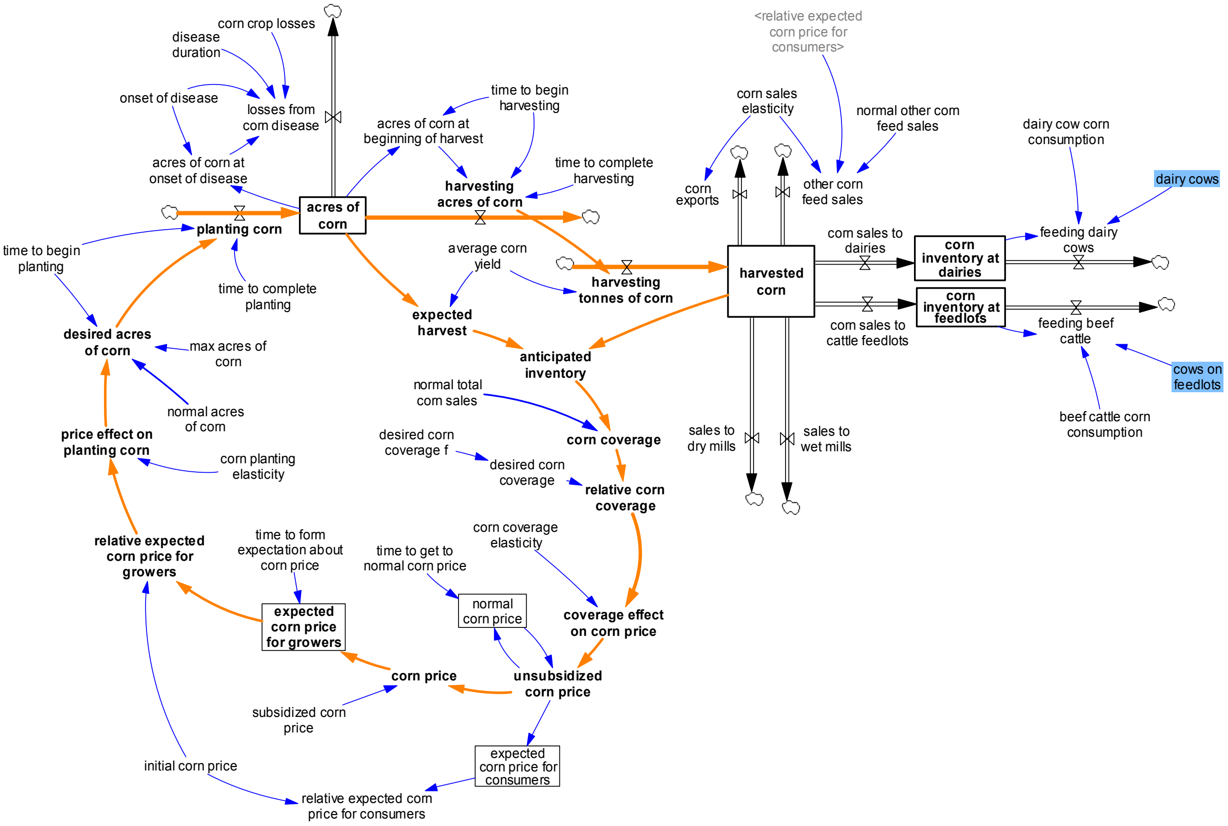


Figure 5. Stock and flow diagram of the corn sector. The variables highlighted in blue introduce feedbacks from the beef and dairy sectors. The negative feedback loop for production is identified by the orange arrows.

Figure 6 shows the stock and flow diagram for the beef sector. The brown arrows indicate the relatively rapid negative feedback loop for consumption and the red arrows indicate the slower negative feedback loop for production. As in Meadows' hogs model, there is also a positive feedback loop in the production cycle (indicated as the green shortcut through the production loop) and operating as follows:

1. As beef prices rise, there is a desire to acquire more breed stock to produce more beef to take advantage of favorable prices.
2. Acquiring more breed stock removes cattle from later in the aging chain. (In reality, ranchers release fewer female calves to market, retaining more of these calves to increase their breed stock.)
3. Cattle removed (or withheld) from the aging chain eventually lowers the beef inventory causing prices to rise.

The prime cattle at the end of the aging chain reside on feedlots and consume a diet that consists mainly of corn feed. The size of this population affects corn consumption. Any seasonal effects in beef production are considered to be secondary and therefore ignored.

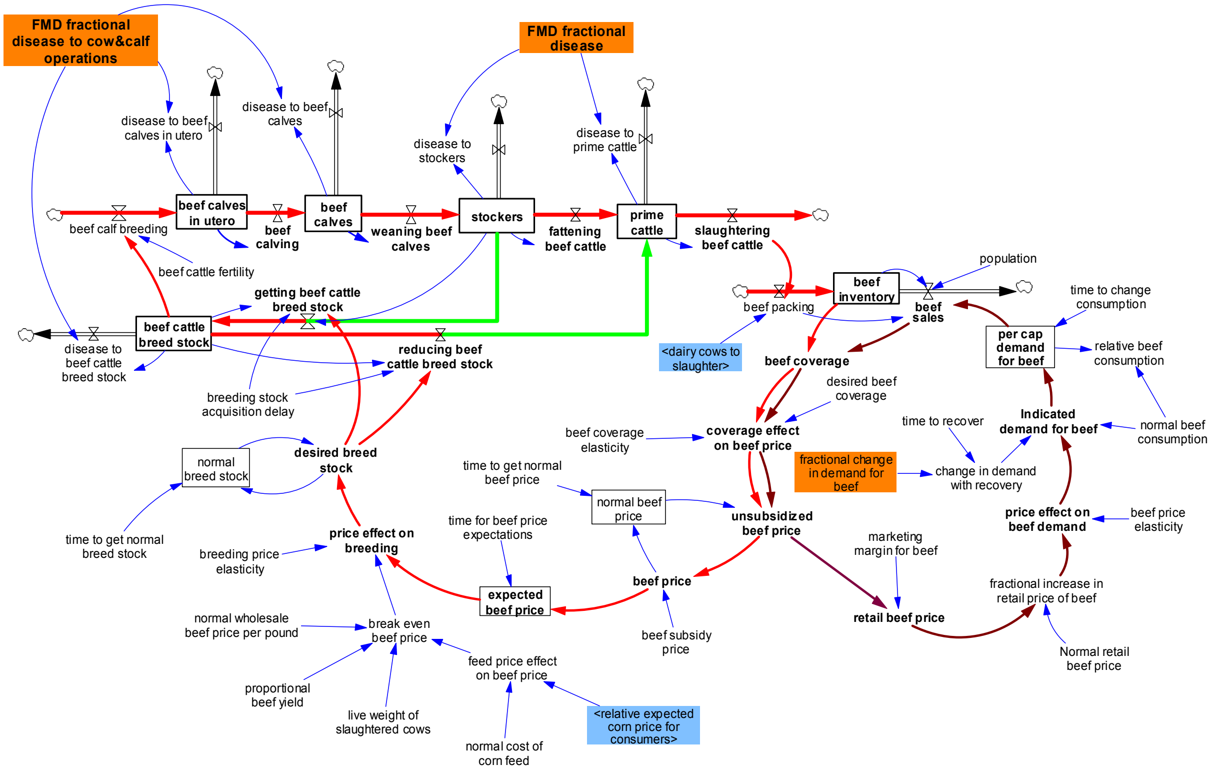


Figure 6. Stock and flow diagram of the beef sector. The variables highlighted in blue introduce feedbacks from the corn and dairy sectors. The variables highlighted in orange indicate where disruptions are introduced. The negative feedback loop for consumption is identified by the brown arrows. Feedbacks in production are identified by the red and green arrows.

Figure 7 shows the stock and flow diagram for the dairy sector. The brown arrows indicate the relatively rapid negative feedback loop for consumption and the red, pink, and green arrows indicate the slower feedback loops for production. Diary production differs from beef (or hog) production in that the breed stock is not at all separate, but instead exists at the end of the aging chain. Cows give milk only after giving birth; milk cows produce both milk and calves. Milk prices affect the desired size of the dairy herd, which affect milk production which, in turn, affects milk prices. The dairy herd size can be adjusted downward through a combination of slaughtering more female dairy calves[2] (pink arrows) or more immediately by culling the milking herd (green arrows). Following the path through the pink arrows first:

1. Lower milk prices leads to a desire to adjust downward the size of the dairy herd.
2. Slaughtering more dairy calves leads to fewer heifers and eventually fewer milk cows.
3. Having fewer milk cows leads to less milk production, thus stabilizing milk prices.
4. But, fewer milk cows also leads to less breeding and eventually through the aging chain to still fewer milk cows and still less milk production (unless the slaughtering of dairy calves is adjusted downward to provide a sufficient number of replacement heifers to stabilize the size of the milking herd).

Now following the green arrows:

1. Lower milk prices leads to a desire to adjust downward the size of the dairy herd.
2. Increased culling of milk cows in the dairy herd leads to less milk production, thus stabilizing milk prices.
3. But again, having fewer milk cows also leads to less breeding and eventually through the aging chain to still fewer milk cows and still less milk production (unless the slaughtering of dairy calves is adjusted downward to provide a sufficient number of replacement heifers to stabilize the size of the milking herd).

Perhaps this failure recognize that reducing the size of the dairy herd not only reduces milk production, but also reduces the size of the breed stock may account for the notorious cyclic volatility in milk prices. Milk marketing boards have been established to smooth milk prices and thereby dampen volatility, but they have been only modestly effective. This could be a fruitful area for additional work to explore this issue further.

As in the beef sector, any seasonal effects in dairy production are considered to be secondary and therefore ignored.

Some Initial Results

The model was initially set in equilibrium. First, let's look at a step change in the demand for beef to see how this perturbation can initiate oscillatory behavior. The 30-year simulation in Figure 8 shows that a 5% drop in demand that persists for one year can cause the population of beef cattle to oscillate with a cycle of about 11 years consistent with data presented in the agricultural literature (e.g., Mathews et al., 1999; Mundlak and Huang, 1996; Rosen et al., 1994; Trapp, 1986; Crom, 1981) and in Sterman (2000) showing that the cattle cycle averages about 10-12 years.

This model can be used to explore a variety of agricultural disruptions such as:

- Change in demand for beef or dairy products
- Significant corn crop losses due to disease or drought
- Forced reduction in beef cattle breed stock as the carrying capacity of western range land is diminished due to drought

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[2] Virtually all male dairy calves are slaughtered because they have negligible value except as veal.

- Loss of exports (such as the U.S. is currently experiencing due to detection of BSE in the state of Washington)
- Widespread cattle disease

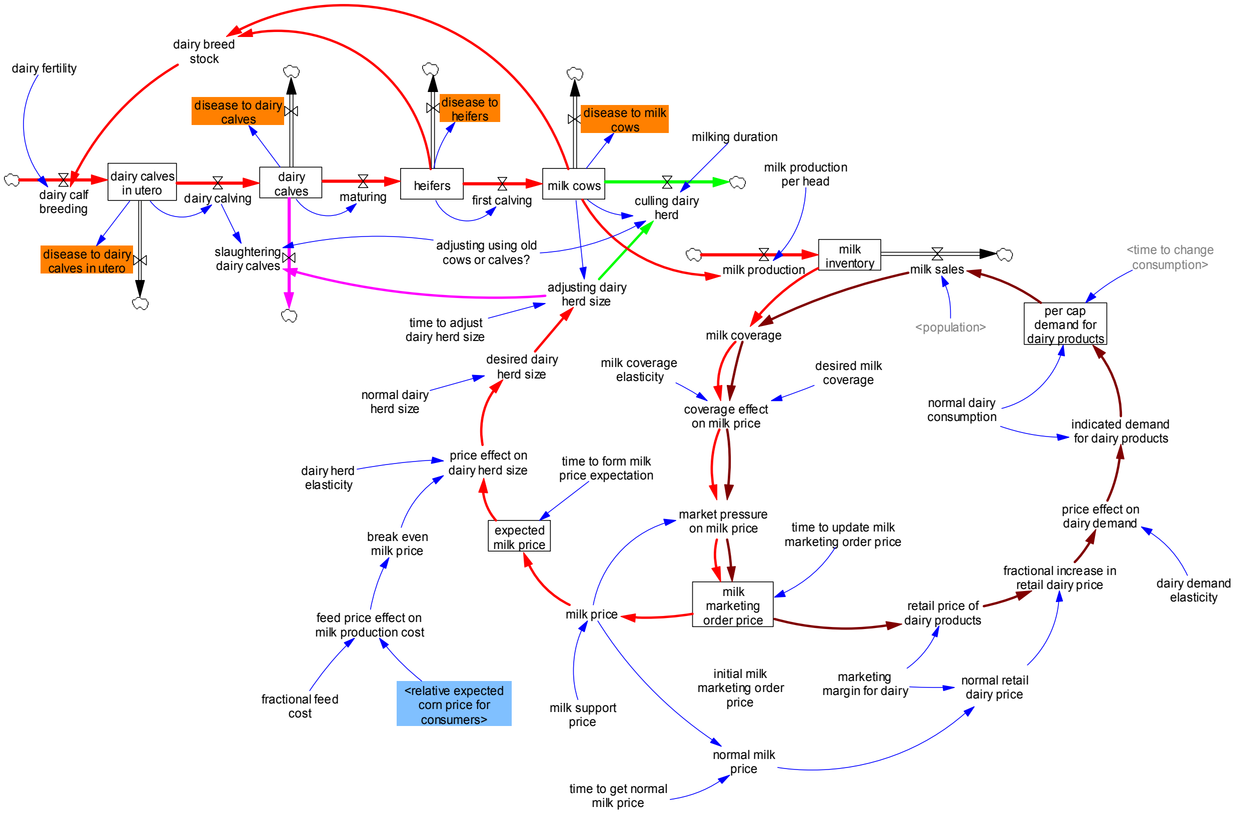

Figure 7. Stock and flow diagram of the dairy sector. The variable highlighted in blue introduces feedbacks from the corn sector. The variables highlighted in orange indicate where disruptions are introduced. The negative feedback loop for consumption is identified by the brown arrows. Feedbacks in production are identified by the red, pink, and green arrows.

As an example of using the model to explore the consequences of widespread cattle disease, we considered an agricultural disruption scenario in which foot-and-mouth disease (FMD) is introduced into the U.S., causing a large-scale outbreak of the disease in both beef and dairy cattle. FMD is a highly contagious viral infection that is transmitted via: direct or indirect contact with infected animals or contaminated materials; aerosol from infected animals; humans carrying FMD virus in their system; contaminated feed; or, contact with contaminated objects. Clinical signs of the disease develop in 3 to 5 days. While he morbidity rate is nearly 100%, the mortality rate is less than 1%. The course of infection is 2 to 3 weeks in cattle, but secondary infection may delay recovery. Lactating animals may not recover to pre-infection production. Beef cattle will lose weight during the course of infection and may not regain weight at previous rates. FMD does not affect humans.

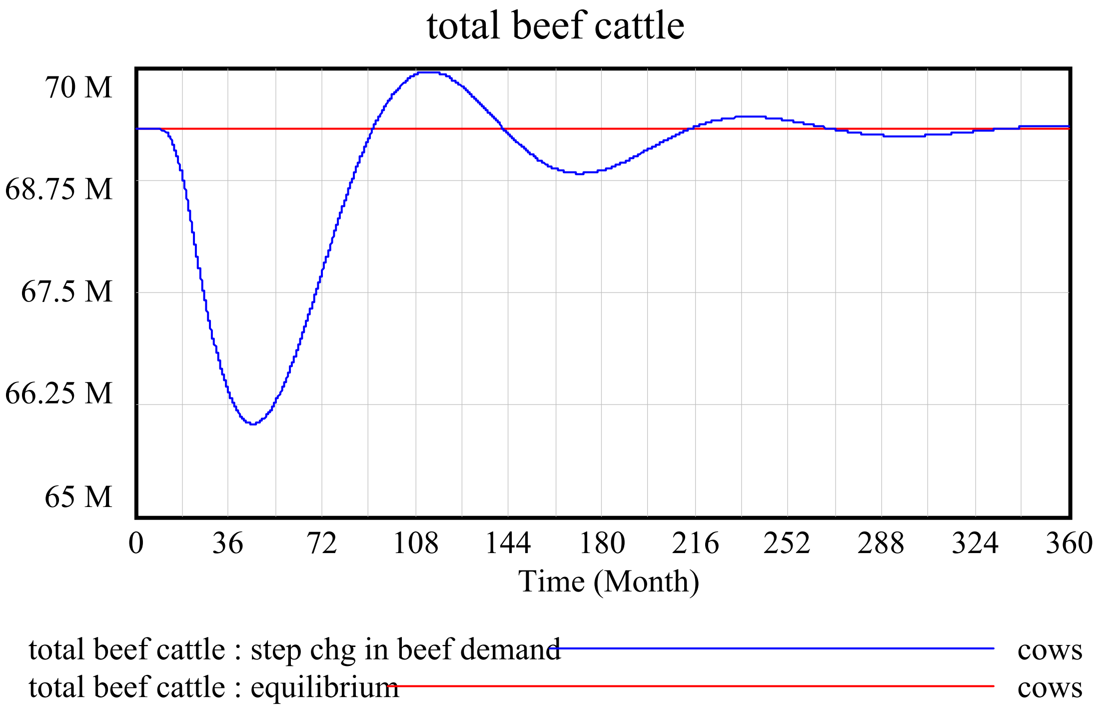

Figure 8. Dampening oscillations in the population of beef cattle initiated by a 5% drop in demand for beef in month 5 and lasting for 12 months.

Existing policy for responding to an outbreak of FMD requires quarantining and depopulating all diseased herds and adjacent herds within the quarantine area. In this scenario, we assume that implementation of this procedure results in reduction of the size of the cattle population by 10%. Furthermore, other nations will impose an import ban will remain in effect until the country can be shown to be disease free for at least 6 months. We assume that this ban remains in effect for 1 year. Since exports account for about 10% of beef sales, we will reduce demand for beef by 10% for one year and assume that domestic demand remains unchanged (except as affected by price). It is reasoned that aggressive quarantining and destruction of herds are warranted to stop the spread of the disease and to reestablish exports as quickly as possible.

The simulation in Figure 9 shows significant oscillations in beef cattle populations and beef prices. Dairy cattle populations show much less oscillation, but milk prices oscillate relatively rapidly with a cycle period of about 4 years. Interestingly, as the length of the export ban is extended, both beef prices and beef cattle populations become much more stable, counter-intuitively suggesting that aggressive action taken to restore the export market as quickly as possible may be counterproductive. A comparison of beef prices for a 1-year versus a 2-year export ban is shown in Figure 10.

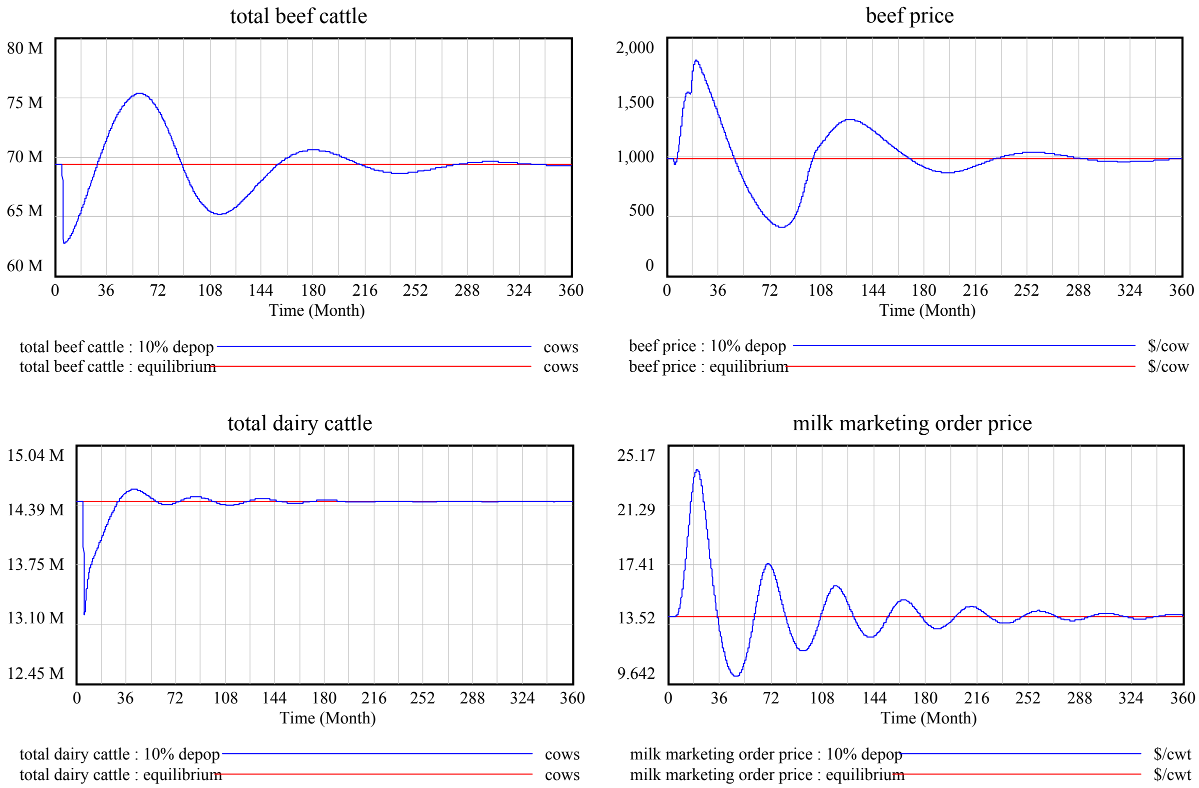

Figure 9. Effects of a nearly instantaneous 10% reduction in the size of the U.S. cattle population combined with a simultaneous 10%, one-year drop in demand for beef (due to loss of exports).

Understanding both the structure inherent in the beef cattle aging chain and the geography of cattle ranching in the American west suggests an improvement to the existing quarantine and depopulation policy. Herds of beef cattle breed stock graze on ranches and public lands that exist predominantly in the lightly-populated, Mountain Time zone region. These herds, together with their calves, are commonly called cow&calf operations. Calves are sold and shipped to stocker and feedlot operations located in the Great Plains. Cow&calf operations tend to be relatively isolated and far less prone to contagion than cattle further along the aging chain that are truck transported through a succession of trading barns, feedlots, and packing plants. So, in addition to relying solely on quarantining and destruction of herds, we propose that perhaps relatively low cost preventative measures to protect cow&calf operations could be instituted. Figures 11 through 13 compare the effects of a 10% cattle loss versus a 10% cattle loss excepting the cow&calf operations. These figures show that protecting cow&calf operations help stabilize beef prices, beef sales, and beef cattle populations respectively. Likewise, corn prices and corn sales to feedlots are stabilized as well. Unfortunately, this policy option does little to help stabilize the dairy sector because the dairy breed stock – the milk cows – are not nearly as isolated from contagion and therefore not as easily protected.

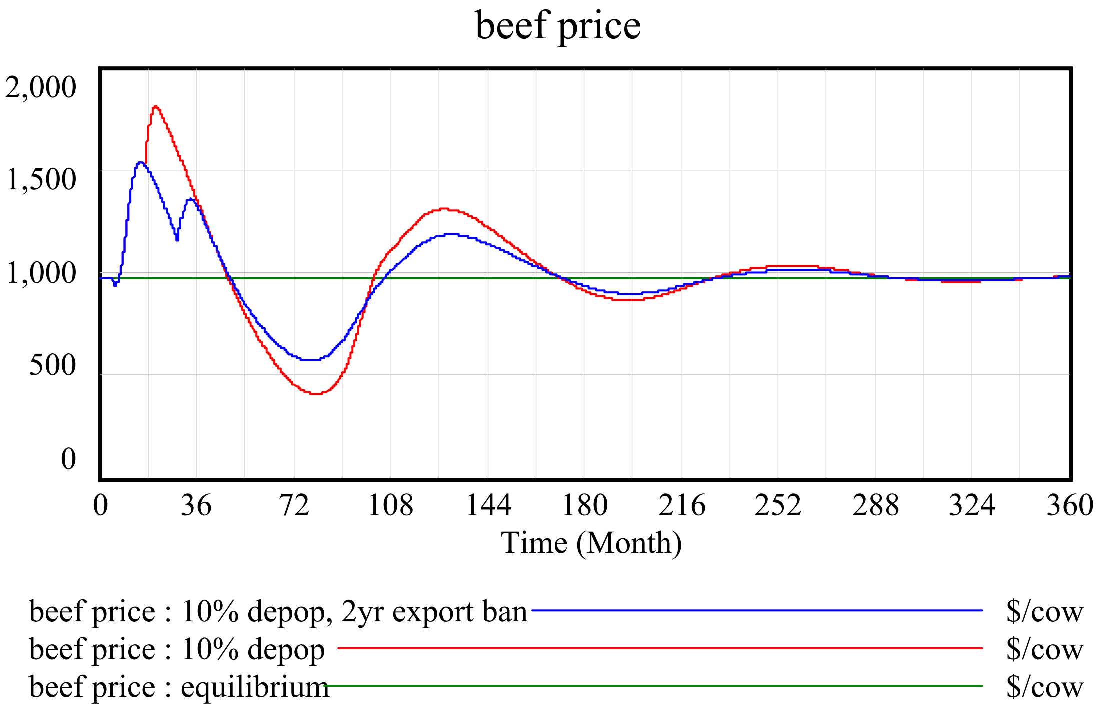

Figure 10. Extending the export ban helps to stabilize beef prices.

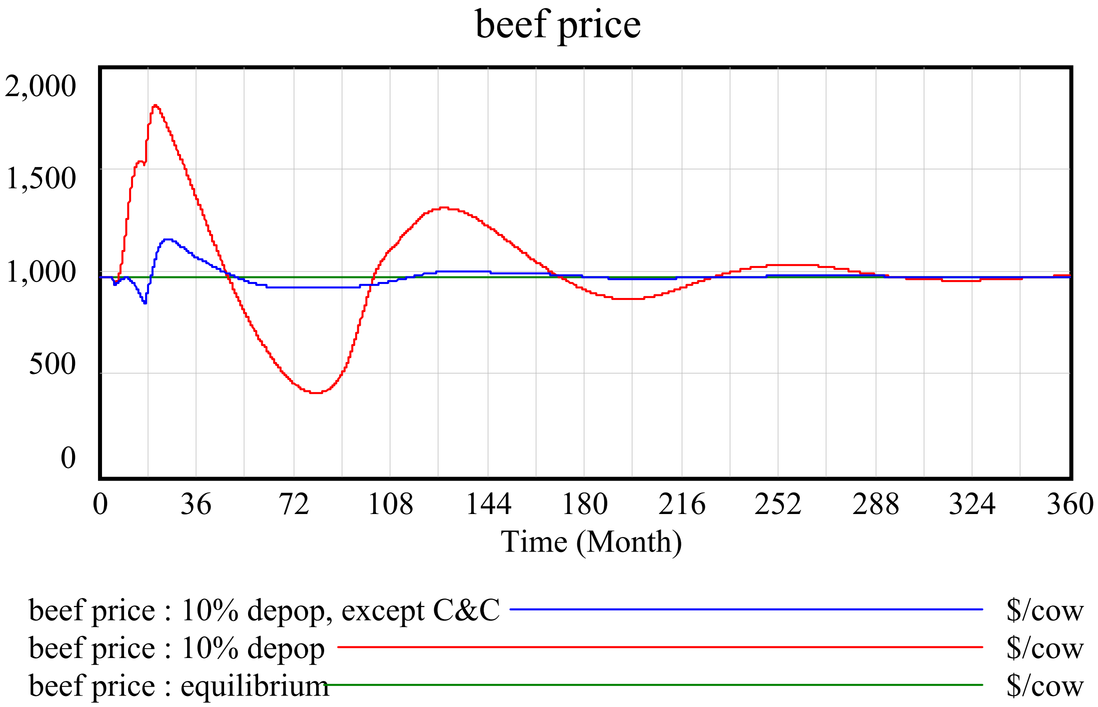

Figure 11. Protection of cow&calf operations helps to stabilize beef prices.

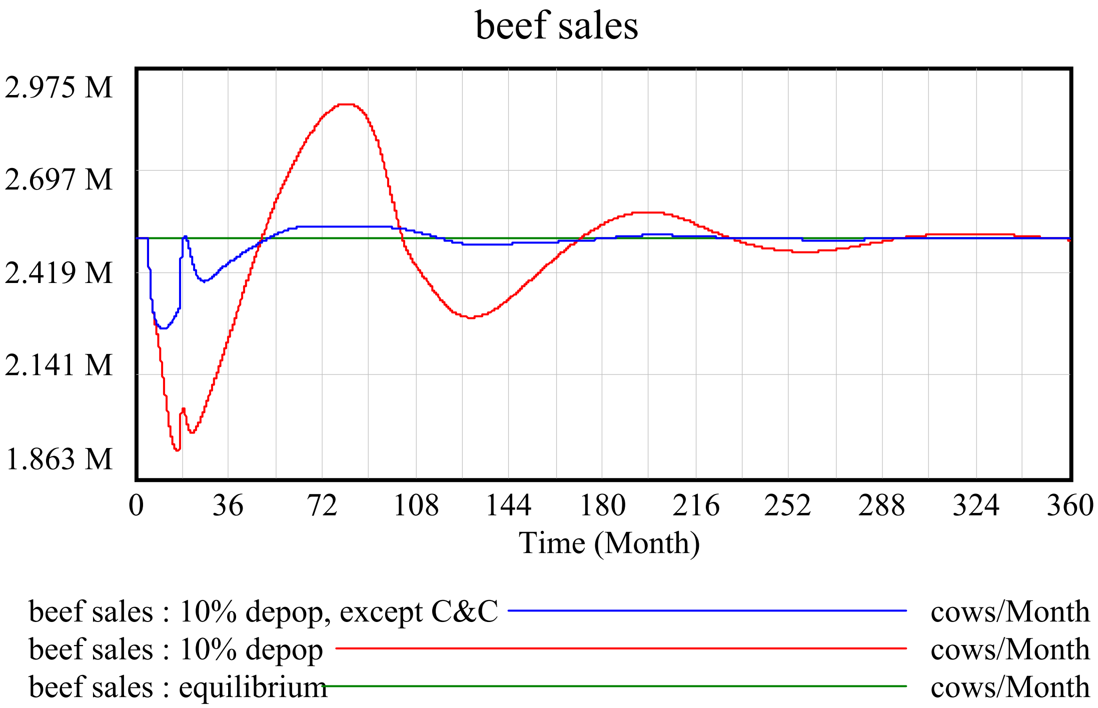

Figure 12. Protection of cow&calf operations helps to stabilize beef sales.

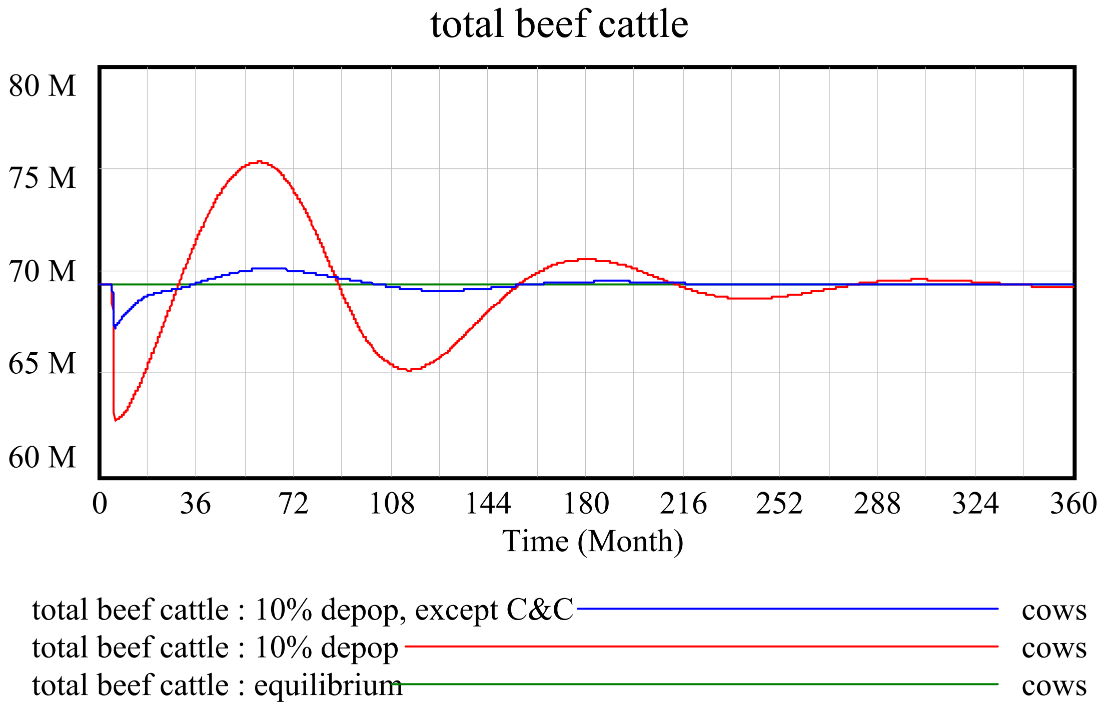

Figure 13. Protection of cow&calf operations helps to stabilize the beef cattle population.

A Concluding Remark

Even though the agricultural commodity model presented here is still very much a work in progress, preliminary model analysis using a single disruption scenario has demonstrated its promise in helping government agencies formulate improved policies for responding to major disruptive events in agriculture.

Acknowledgements

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