Decision Support System for Soybean Rust (*Phakopsora pachyrhizi*) Management using QnD

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Abstract

The objective of this project is to design a decision support system for soybean rust management using gaming software that incorporates farmer's decision making in the face of risks from soybean rust. Learning from past actions and neighbor's actions are also incorporated. Farmers observe rust outbreak in the current and past periods and decide over how much of land to allocate between soybean, corn and other crops. This decision is influenced by maximization of expected profits criterion which entails crop rotation choices that are based upon perceived risks, yield drags and input costs from altering optimum rotation patterns. Adoption of new technology in terms of selecting better rust management practices is also analyzed in an adaptive management framework. The software meets the need of guiding policy formulation besides training stakeholders in making economically sound choices in the absence of empirical data over pest infestation.

Introduction

Soybean rust, a disease of the soybean and several other plant species, has been threatening the US soybean crop since it arrived in 2004. Though the threat was reduced in 2005 due to limited infestations during the crop season, potential for the pest becoming endemic are serious and call for long term planning to manage this pest. Soybean rust is chiefly windborne and is capable of trans-continental migrations helped by favorable events such as hurricanes. In fact, hurricane Ivan of 2004 is suspected for bringing soybean rust from South America. Soybean rust could cause significant damages to the US soybean crops and available estimates in the literature project losses of up to US $7.2 billion/year from the disease (APHIS USDA 2004).

Management of soybean rust would require significant private participation involving soybean growing farmers in the affected States and collaboration amongst various States (and their respective area specialists) in order to monitor and control its seasonal migration across regions. Due to its ability to survive in cool and wet climates, it is possible for the rust to over-winter in the Southern Sates and infest soybean crops during the growing season. Kudzu, a secondary host of the rust, is predominantly found in the Southern States and could greatly assist in the long term establishment of this pest. Management of soybean rust would require understanding the cropping decisions, preventive and curative decisions and insurance options for the farmers and being able to influence such choices through timely policy interventions. Crop rotations, such as switching between soybean and corn (or other crops) and adequate precautionary steps such as spraying of plants with fungicides could significantly reduce the damages from soybean rust. Yet, crop rotations are a function of several economic criteria such as differential economic yield between various crops per acre, crop prices, yield drags and additional input costs involved in sub-optimum crop rotations and the risk perception of the farmers. Similarly, decisions over how much or whether or not to spray are influenced by risk perceptions and could vary from location to location based upon farmer and regional heterogeneity. Preventive versus curative spraying is an additional choice the farmers could exercise. Adaptive management of crops faced with the threat of invasion can be expedited by public polices that reward socially optimum practices. For this to be possible, an understanding of farmer's learning capabilities under various infestation scenarios is crucial as it would help policy makers be a leg up in terms of public inducement programs. One crucial learning process could be the decision over preventive spraying based upon the latest spore finding at a location of *x* miles from the farmer's plot. This distance is bound to stabilize over time through learning and adaptation.

Soybean rust requires a paradigm shift in invasive species management. Invasive species must be tackled at their source of introduction rather than waiting for them to show up in regions where they could be potentially harmful to agricultural crops. Kudzu, a secondary host of the *sbr*, is a key plant that could ensure its survival in the winter season, especially in South Florida. Therefore, there is a need to understand the science behind the chances of survival of *sbr* in the South and incorporate that into a decision support tool.

While some work has already been done (Livingston et al. 2004, Roberts et al. 2006), that predicts the damages from *sbr* under various control scenarios, the literature is still lacking in the knowledge over the capability of farmers to manage the risk of *sbr* and being able to learn quickly to adapt to such risks through change in cropping pattern and *sbr* control technology. Further, there is also a need to help the farmers get trained in rust management by getting sound scientific advice over the sbr spread probabilities and the choice of management tools that optimize economic returns. Due to lack of empirical evidence of rust impact within United States, real time tracking and guidance is the key to managing *sbr*. Consequently, there is a need for software that could keep abreast of year to year seasonal spread of sbr and provide guidance to stakeholders over the choice and timing of management tools. This paper presents the details of a software being developed to meet the above mentioned needs. The methodology involves relating farmer's actions in terms of agricultural and invasive species management choices to consequences over profitability and pest spread outcomes. The biology of sbr spread and its impact over crops provides the crucial linkage between management choices and outcomes. By repeating the management outcomes over hypothetical scenarios that are grounded in real time observations, the tool offers a trial and error type learning support for the stakeholders. Simulating decisions based upon spatial and temporal spread of the pest and also upon the actions of neighboring farmers, the behavioral responses of the farmer could be brought to light. Knowledge of learning behavior could provide crucial feedbacks to policy makers and guide the choice of policies that further enforce such behavior.

Before proceeding to the model, a brief review of the biological and economic issues related to soybean rust is in order. After which, we present a detailed explanation of the QnD software, the model, the assumptions involved and some preliminary results.

Biological Background

Soybean rust is a fungal species. There are two types of this species; *Phakopsora pachyrhizi (*Asian rust*) and the Phakopsora meibomiae* (The new world type). It is, however, not easy to distinguish between the two species without the use of molecular techniques (Sweets 2002). Soybean rust mostly affects the leaves of the host plant, producing powdery pores that reduce the photosynthetic capability of the plant thus causing reduction in seed numbers and weight (Sweets 2002). Of the two, the Asian rust has been found to be more damaging. This is found in Japan, Australia, central and southern Africa, etc. The new world type is found in the Caribbean and Central and South America (Sweets, 2002). Soybean rust was first detected in Japan in 1902, from where it spread to other parts of Asia (India 1951), Australia, Africa (Kenya, Rwanda, and Uganda, 1996) and South America. It was detected in Hawaii in 1994.

Soybean rust has already arrived in the US, detected first in Southern US in 2004[1]. Its current day to day status is being monitored by APHIS and can be found at USDA's soybean rust website (at www.sbrusa.net). As of November 2005, North Carolina had 14 infected counties, Alabama 29, Florida 23, Georgia 34, Mississippi 2, South Carolina 18, North Carolina 14, and Louisiana had 1 infected county.

Soybean rust is chiefly windborne and the pores produced by the fungus can be readily carried through wind and deposited in locations very far way. The Asian soybean rust which affects 95 species of plants including Soybean, has drastically affected crop yields in Asia. These spores quickly establish themselves in new environments under favorable conditions (Nagarajan and Singh 1990). The ideal conditions of the spread of

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[1] *"The most likely scenario as to how soybean rust arrived in the continental United States is via Hurricane Ivan. Ivan formed in the Atlantic in early September, brushed the South American coast, and proceeded to strike the southeastern United States, carrying rust spores from Colombia and Venezuela" (Hart 2005).*

soybean rust are cool (below 82 F) and wet weather. There are 30 species in 17 genera of legumes that are hosts to soybean rust. In the US, Kudzu is considered to be a potential host to the rust[2]. The establishment of soybean rust could have serious implications for the US agriculture. Consequently, economic factors linked to its spread and damages are of key importance.

Economic Issues Related to Rust Management

Cropping patterns can severely influence damages from soybean rust. In South Africa in 2001, the loss in yield from soybean rust was up to a hundred percent in regions where farmers did not rotate their crops and practiced mono-cropping (APHIS USDA 2004). In the USA, total losses to crop yield may reach up to 50% in regions where climate is conducive to their growth. Projections of economic damages reveal a loss of US $7.2 billion/year from the disease (APHIS USDA 2004). Computer simulations have predicted yield losses up to fifty percent in Southern Florida due to its warm climate (Corn and Soybean Digest 2003). The South American Countries lost $1 billion in 2002 to Soybean Rust (Lamp, 2003). Brazil, which harvested $11.5 billion worth of soybean crops in 2002-2003, had nearly 80% percent of its soybean crops treated with fungicides. This led to an added cost of $40-50 per hectare to its production costs (Reuters, November 14 2003).

Fungicides have been found to be effective but may prove costly to small farmers. Other methods of its control include host eradication (weeds, etc.), biological control and

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[2] More information related to Kudzu population in the US and rust findings in those areas can be found at the University of Illinois at Urbana Champaign’s website: (http://soyrust.cropsci.uiuc.edu/ed_mat/rust-confirmations.pdf).

development of more resistant soybean varieties. The cost of fungicide application may be enormous for marginal farmers as it might take up to three applications at a cost of $15 per acre to control the pest (Corn and Soybean Digest 2003)[3]. There is very limited scope for preventive efforts as the pores have the ability to transport themselves through wind over vast measures of space. Preventive measures may be ineffective for two reasons. First, there are no known soybean varieties that have genetic resistance to the pest. Further, the conditions suitable to soybean have also been found to be suitable to the rust (Corn and Soybean Digest, 2003).

Soybean and Corn Yield Functions

In our model, the State-specific yield functions for soybean and corn are based upon an ERS report by Teigen and Thomas (Teigen and Thomas 1995). The non-linear relationships between temperature and precipitation explain most of variations in the yields in corn and Soybean (Teigen and Thomas 1995). Using this approach, Teigen and Thomas estimate the yield functions for soybean and corn for the primary production states within the US. The data set consists of an aggregated monthly temperature and precipitation value at the State and regional levels. Other key factors included in the model are time trend and acreage. They find that the corn yields have increased at an average of about 1.8 bushels per year for the period of 1950-1993. The impact of rainfall is significant for the months of July through August on crop yields, whereas the months

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[3] "*The Environmental Protection Agency (EPA) has registered three chemicals--azoxystrobin, chlorothalonil, and pyraclostrobin--for the treatment of soybean rust. These chemicals are preventative treatments in that they protect soybean plants from infestation and limit subsequent rust development. Soybean rust spreads by spores. There are, however, restrictions on the extent and number of applications of these chemicals and not all States approve these chemicals.*" (Hart 2005)

of Jan through May have insignificant impacts. Both the temperature and precipitation impacts on yields are quadratic in nature. The rainfall and temperature data is converted into Z-scores which represent variation from the long term mean divided by the standard deviation.

Soybean and Corn Prices

Historical prices for Soybean and Corn are available at the NASS. The US is no longer the dominant producer of soybean and its prices are now jointly determined by the South American production and the US stock to use ratio. An ERS study finds that an increase in one percent of South American soybean production depresses US prices by .25 percent. This effect includes the negative impact of South American production of soybean on US stock to use ratio (.4 percent to every 1 percent change in South American production) and the subsequent impact of reduction in stock to use ratio on US prices (.5 percent to every one percent change in stock to use ratio).

Options for sbr management

Acreage Allocations between Soybean and Corn

The risk of economic loss from soybean rust can be mitigated by planting corn (and other crops) in place of soybean. The current practice of a 50:50 corn: soybean crop rotation reduces the need for soil amendments and helps maintain soil fertility and yield. The decision to increase the corn rotation will also depend on relative crop prices and the effect of the rotation on input costs and yields.

Treatment Decisions for Soybean Rust

Both preventative (pre-infection) and curative (post-infection) fungicide spray options are available for treating soybean rust. Application timing is critical in the effectiveness of these options. Daily spore monitoring reports can aid farmer preparedness. Farmers can purchase insurance against *sbr*, however reimbursement for damages may dictate that the farmer follow ‘good management practices,’ i.e. timely fungicide application. The various stages of soybean plant growth are classified as V1 through Vn and R1 through R8, where V stands for the vegetative stage and R for the reproductive stage. It is the reproductive stage of the plant growth when it is most vulnerable to infestation from the rust. R1-R2 are the flowering stages, R3-R4 for pod development, R5-R6 seed development and R7-R8 are the maturity stages. Late R4 through the early R6 stages are the most vulnerable periods for rust infestation and fungicide application is most recommended within this time period.

Insurance

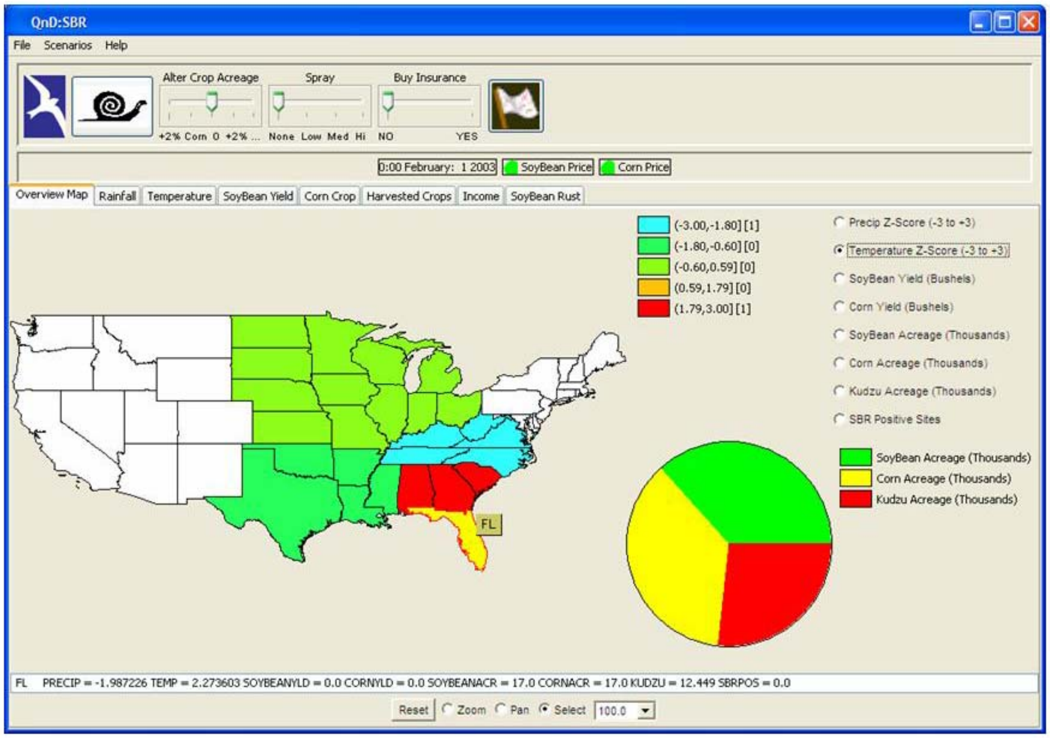
There are two types of insurance available to farmers: group insurance and individual insurance. Individual insurance reimburses the farmer for losses exceeding the deductible. Estimation of losses is based on yield and revenue history. Group insurance ties reimbursement payments to historic county yields and a minimum yield cutoff. Both options may require farmers to follow disease prevention and protection protocol in the event of a spore infestation. The insurance protection may erode over time if rust becomes endemic and insurance premiums and deductibles rise.

QnD Software

Questions and Decisions Modeling System

The *Questions and Decisions* ™ (QnD™) model system (Kiker *et al.*, 2006) was created to provide an effective and efficient tool to integrate ecosystem, management, economic and socio-political factors into a user-friendly model framework. The model is written in object-oriented Java and can be deployed as a stand-alone program or as a web-based (browser-accessed) applet. The QnD model links spatial components within geographic information system (GIS) files to the abiotic (climatic) and biotic interactions that exist in an environmental system.

The model can be constructed using any combination of detailed technical data or estimated interactions of the ecological/management/social/economic forces influencing an ecosystem. The model development is iterative and can be initiated quickly through conversations with users or stakeholders. Model alterations and/or more detailed processes can be added throughout the model development process. QnD can be used in a rigorous modeling role to mimic system elements obtained from scientific data or it can be used to create a “cartoon” style depiction of the system to promote greater learning and discussion from decision participants.



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FL    PRECIP = -1.987226 TEMP = 2.273603 SOYBEANYLD = 0.0 CORNYLD = 0.0 SOYBEANACR = 17.0 CORNACR = 17.0 KUDZU = 12.449 SBRPOS = 0.0
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Figure 1: Screen capture from the QnD: SBR demonstration version (Kiker and Ranjan, 2006).

The QnD system has two parts: the game view and the simulation engine as shown in Figure 2. The game view has several types of outputs that can be configured by the user via XML (e**X**tensible **M**arkup **L**anguage) file inputs. By presenting the outputs as selectable, QnD allows users to choose how they want to see their output, including the following output options:

- GIS Maps that are updated on each time step
- Warning lights that change at user-selected critical levels
- Mouse-activated charts and text for individual spatial areas (pie charts and text line descriptions)

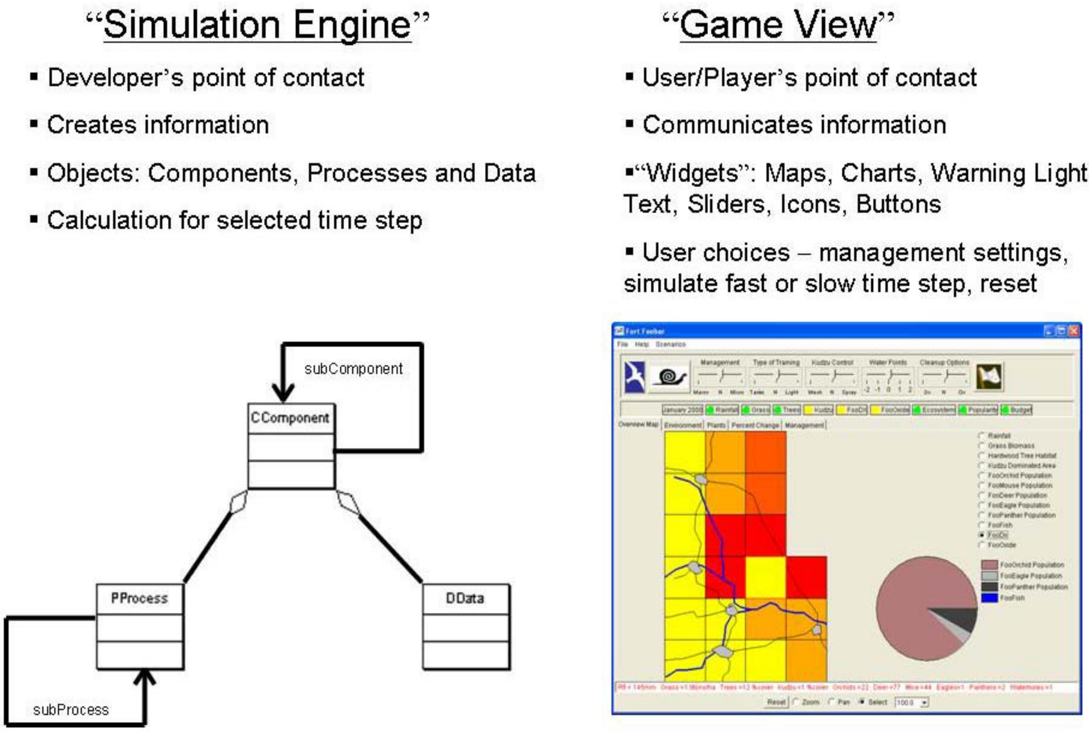
- Time-series charts (listed on several tabbed pages)
- Text output files (in comma separated format)

The simulation engine of QnD is made of objects linked together into simple or complex designs, determined by the needs of decision participants. The most elemental objects of QnD are Components, Processes and Data. A Component is an object that is of interest to the user. Processes are the actions that involve Components. Data are the descriptive objects assigned to Components. If one uses parts of grammar as an analogy, Components are the nouns. Processes are the verbs. Data objects are the adjectives or adverbs. Components objects are spatially situated into the virtual QnD landscape and can interact with each other over space and time. With the QnD object framework, both simple and complex designs are possible. In more complex designs, building block components and processes designed as clusters of subcomponents or sub-processes.

Upon startup, specialized internal QnD objects read the relevant XML input files and create all the engine parts (Components, Processes and Data) as well as the game view (maps, charts and management options) required for the simulation. Once all the necessary parts are created, QnD is “played” much like any other computer games. Users can manipulate the game view in the following ways:

- Set some management options (using the slider bars)
- View the map page and switch between maps (with radio buttons)
- View the various Chart pages (with the chart tabs)
- Simulate a time steps at user-defined levels

- Reset the game to the startup



“Simulation Engine”

- Developer’s point of contact
- Creates information
- Objects: Components, Processes and Data
- Calculation for selected time step

“Game View”

- User/Player’s point of contact
- Communicates information
- “Widgets”: Maps, Charts, Warning Lights, Text, Sliders, Icons, Buttons
- User choices – management settings, simulate fast or slow time step, reset

Figure 2. QnD model structure (from Kiker et al., 2006).

Management settings are applied to the current time step that is activated by mouse-clicking on either of the two time step buttons. After clicking on the time-step button, results of the simulation are applied to the various output devices (maps, charts, warning lights, text files etc…). The user may explore the system outputs, choose new management options and continue with the simulation. Certain end points can be created to show various ramifications of management actions. In Kiker *et al.* (2006), QnD end points showing ecosystem destruction, bankrupt financial status or employment termination were used to show the various end points of ecosystem management in African savanna ecosystems.

SCENARIO AND MODEL DEVELOPMENT

The QnD model has been developed as a useful tool embedded in a larger process of stakeholder and public participation when utilized to generate questions and decisions for complex environmental management (Kiker et al, 2006; Kiker and Linkov, 2006). Development of a QnD game and its application is one potential way to view a complex environmental problem situation from a variety of technical, social and cultural perspectives.

QnD and Scenario Planning

A QnD scenario model can be used to facilitate dialogue and learning at several stages through the scenario planning process (see Figure 3). The QnD development methodology is flexible and responsive enough that it can be used iteratively throughout the entire scenario development process, or as a quick snapshot at any one stage. The extent of application is at the discretion of the scenario development team; the model does not need to be included from the beginning, nor does it need to be used through the entire process to the end. QnD provides unique benefits when used at various points of scenario development, as discussed below.

Initially QnD can be used to assist with setting the agenda, at the same time that individual interviews and group brainstorming is taking place. The model development process becomes a form of analyzing the current situation by finding critical driving forces and main concerns. Through the participative process used to create the model, stakeholders discuss and debate the current situation. The result is a working model which reveals the implications of qualitative and quantitative information, including participants' assumptions and worldviews. The QnD model that is built during this initial phase is called Version Zero.

As scenarios are being structured and story lines developed, the QnD Version Zero can be adjusted to reflect the different worlds that are being created. The model is useful at this stage of development to test the first generation of scenarios for internal consistency and plausibility. The questions that need to be answered in order to build the model and work with the game interface reveal any inconsistencies that exist in the story lines. The model that is developed at this phase can be called Version One. While the QnD model can be used as scenarios are being developed, the model can also be developed when scenarios are already in place. Once scenario story lines are finalized, QnD is used to create an interactive scenario environment. If Version Zero and Version One were developed earlier in the process, then these versions are adjusted to reflect the key drivers and story lines that have been chosen, resulting in Version Windtunnel. If QnD is used for the first time at this stage, a new model is quickly developed around the key drivers and story lines. QnD Version Windtunnel creates an interactive scenario environment which is used to windtunnel or trial strategic options in order to determine the implications of various potential decisions in the different scenario story lines. The effects of various strategic options are reported as model results used to evaluate each option against the conditions in each scenario story line. By interacting with the QnD game interface, stakeholders are able to windtunnel potential management decisions, searching for actions that are more robust when played out within the conditions of different future worlds described in the scenarios.

The QnD Version Windtunnel continues to be used once implementation begins. As action plans are implemented, the model is updated with monitoring data and the game interface is used to trial changes to action plans. By using a QnD Scenario Model, the future worlds created in the scenario story lines are maintained in a working game which makes it possible to continually interact with the lessons learned during the scenario development process. The lessons are not lost as key drivers and variables are available in a useable format for stakeholders at all levels of decision making.

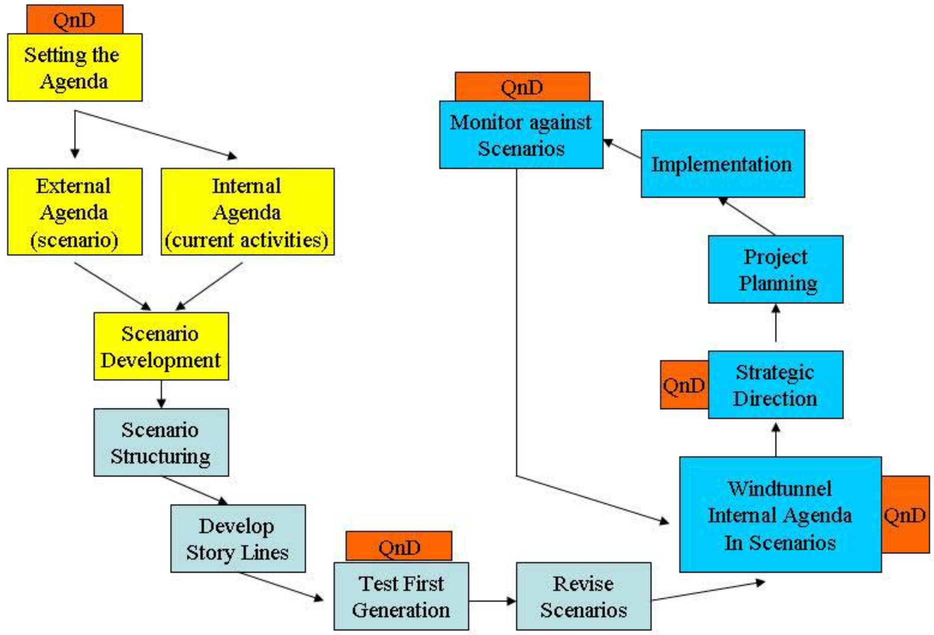


Figure 3. Overview of the scenario planning process integrated with the QnD model.

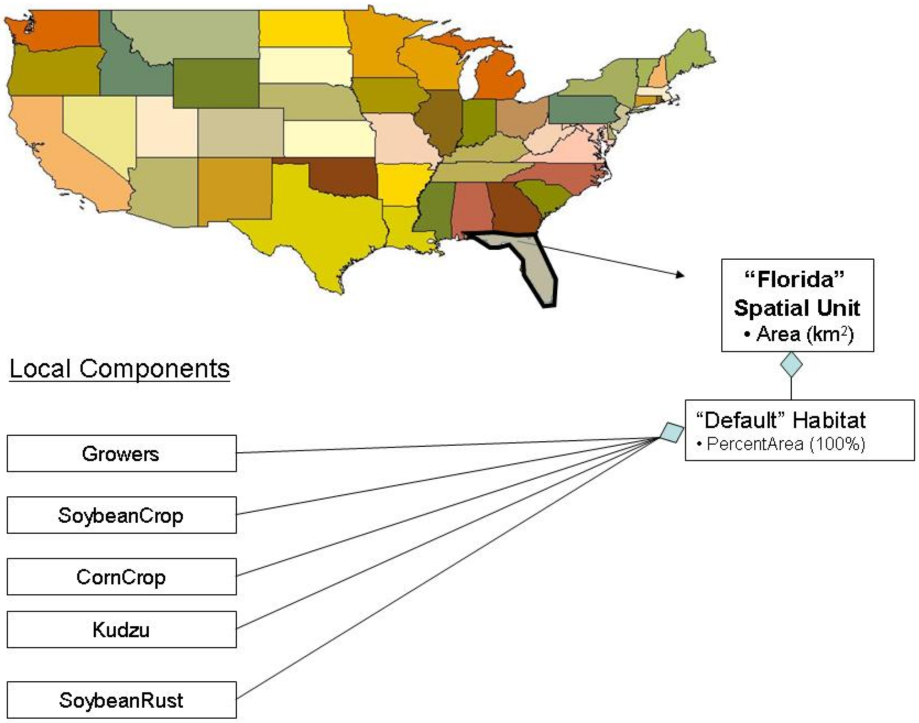


Figure 4: Spatially explicit objects at the state scale using Florida as an example.

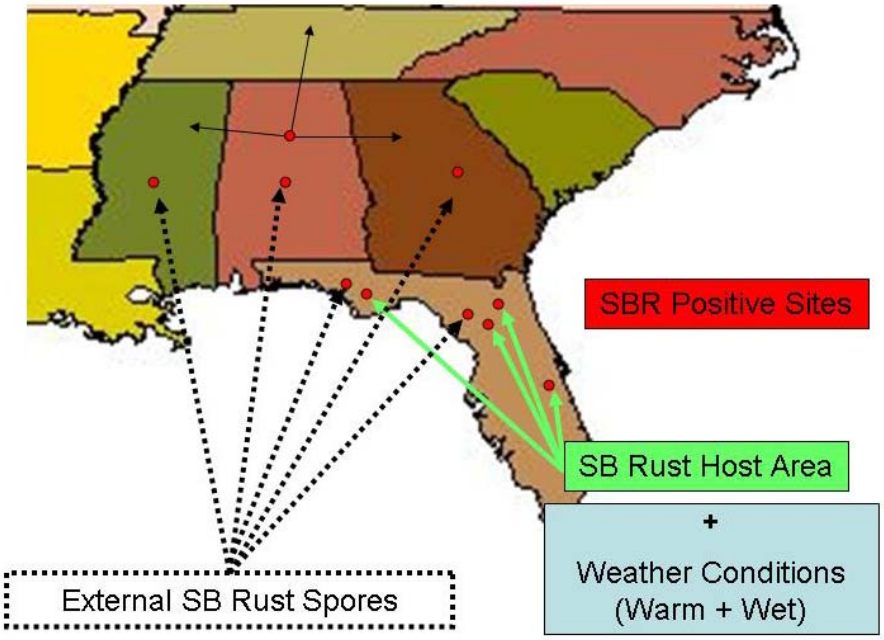


Figure 5: Soybean Rust sources and spread diagram.

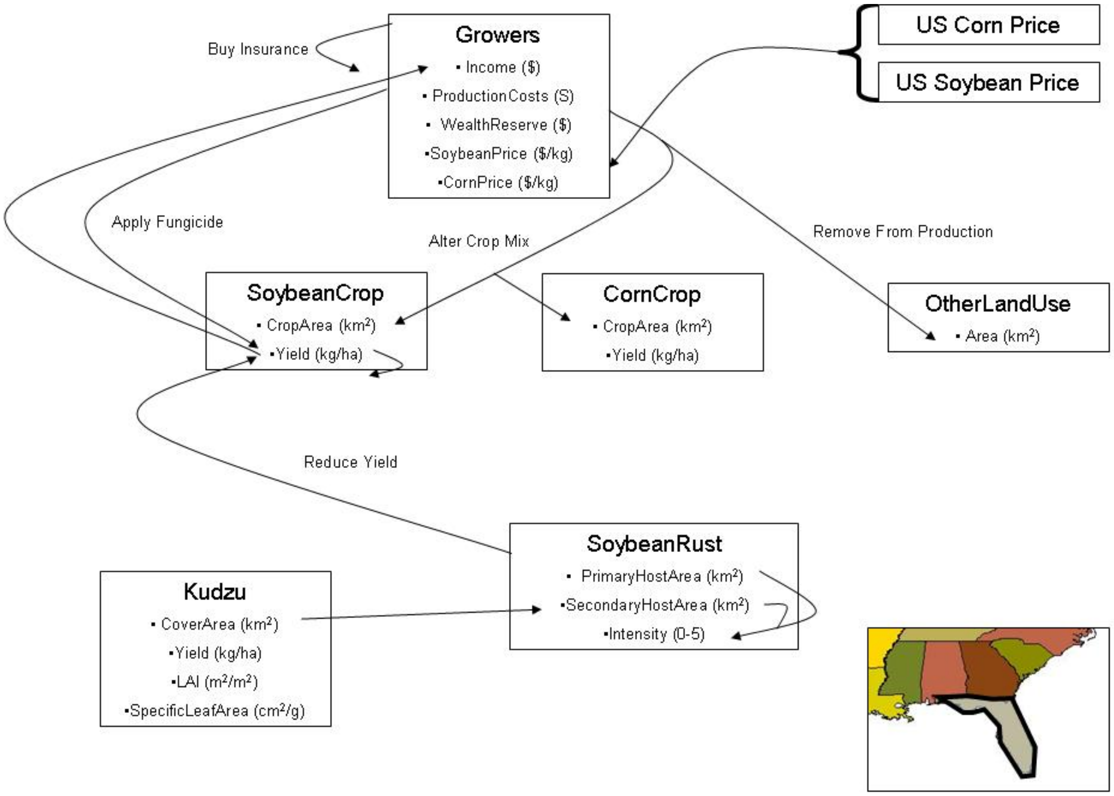
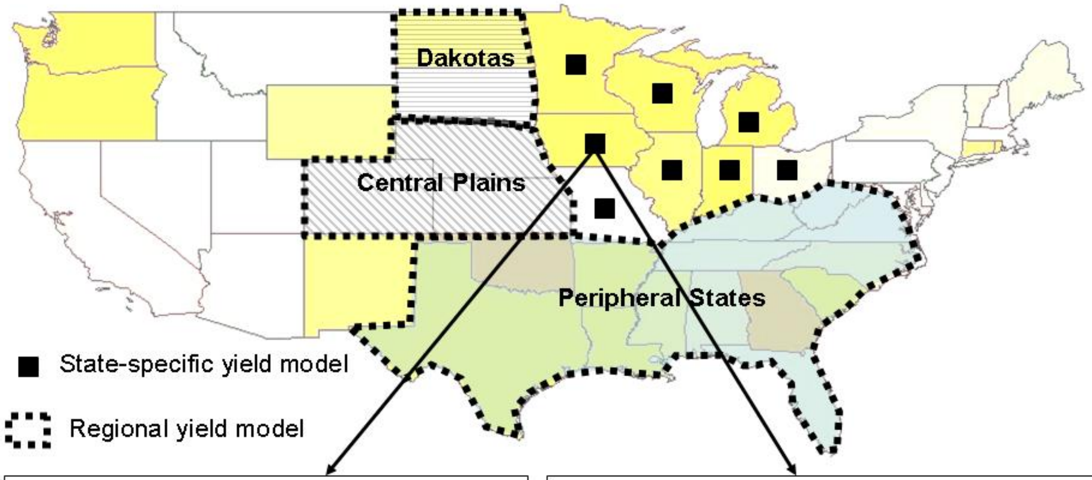


Figure 6: Local Component Interactions within a state



Effect of Weather on Iowa Corn Yield:

$$\begin{aligned} Eff_{corn} = & -3.1087(\mathrm{Pr}_{May})^2 + \\ & \mathrm{Pr}_{Jun}(-2.9105 + 7.3839(Tm_{Jun})) + \\ & \mathrm{Pr}_{Jul}(5.9502 + 5.7697(Tm_{Jul})) + \\ & 5.9023\,\mathrm{Pr}_{Aug}\,Tm_{Aug} \end{aligned}$$

Where Pr_{month} = Rainfall Z score for the designated month,
Tm_{month} = Temperature Z score for the designated month

Iowa Corn Yield (bu/acr):

$$Yld_{corn} = Eff_{corn} + 1.79986(Yr - 1990) + 131.81738$$

Figure 7. State and region -specific crop models are adapted from Teigen and Thomas (1993). The weather effects and yield functions are listed for Iowa.

Results

The simulation analysis involves the farmer simulating his soybean yield and revenue outcomes through the selection of a set of options which are both spatially and temporally defined. Figure 8 shows an example set of QnD:SBR yield outputs for soybean for Iowa and Florida spatial areas (upper graph) for one season. In addition, the lower graph displays the various precipitation inputs in terms of the Z-Score (+3 for extreme wet conditions, 0 for median conditions and -3 for extreme drought).

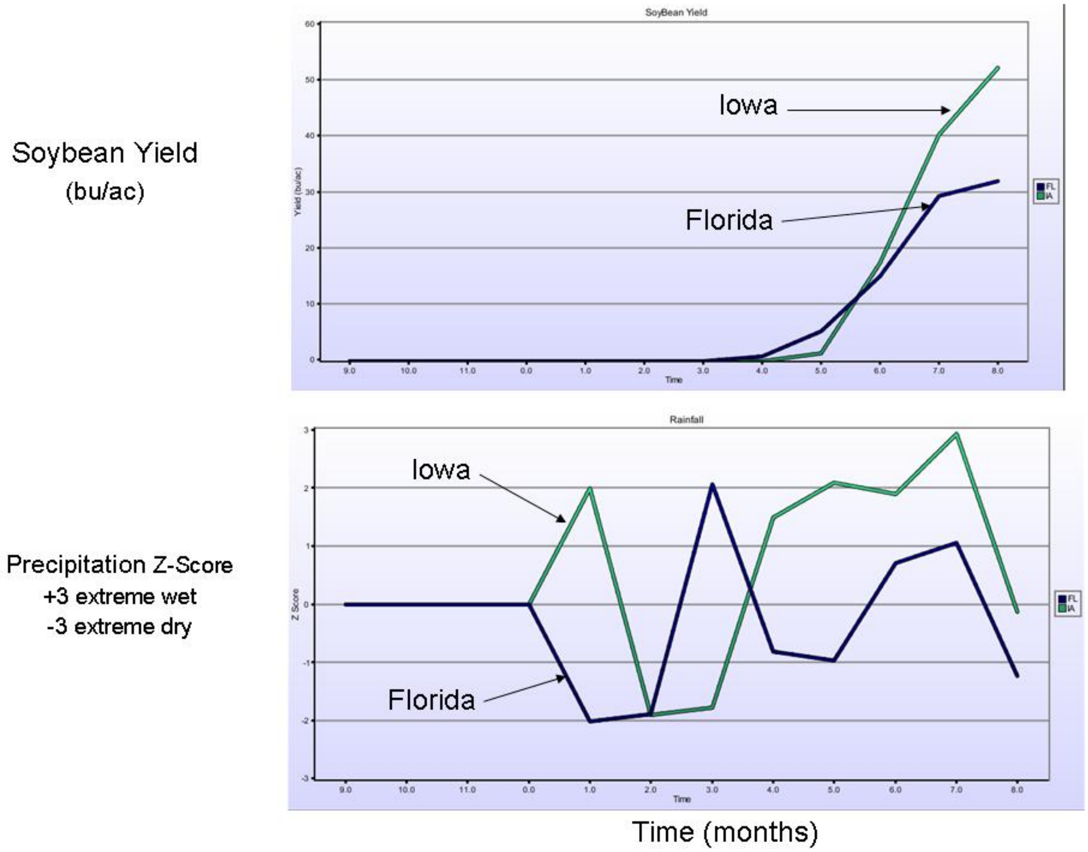


Figure 8. Example QnD:SBR results showing simulated soybean yields for Iowa and Florida. In addition, the monthly precipitation Z-Score is provided to show the influence of rainfall over the season.

Within the QnD:SBR model, the graphs in Figure 8 scroll along, showing the newest month's simulation while displaying the last twelve months of climate and yield data. Additional charts can show total production costs, corn yields, total profitability, soybean rust sites and other data of interest to the player. QnD's modular structure allows any data object to be displayed within a map, time series, warning light, text or output file value. With this modularity, specific interface options can be created quickly to suit various player preferences.

Using the integrated weather, yield and SBR information over each month, a farmer in the Heartland region would have the option of observing the pest spread through the southern regions over each month. His early decisions would involve crop choices between soybean, corn and others. Once crops have been planted, his next set of choices would be to scout the fields for SBR frequently and apply preventative spraying promptly. He would also of the choice of purchasing insurance at appropriate times. Finally, curative spraying would be applied. This process is simulated for a distribution of pest spread which is randomly generated but adheres to the accepted limits within the region. Other uncertain parameters over which the farmer may have no control are prices, weather parameters and neighboring farmers' actions. Simulating over this entire range of uncertain parameters trains the farmer in generating a range of outcomes and makes him conversant with the consequences of his actions fairly quickly.

Upon full development, the model would be capable of performing the above functions for all relevant regions in the US. Further, possible extensions to incorporate use of advanced markets and application to other related invasive pests would be explored. Some of these extensions are detailed below.

Future Extensions

Use of Futures and Options to Mitigate Risk

Increase in global supply combined with the threat of soybean rust for soybean has lead to increased price fluctuations for soybean. After the first discovery of soybean rust, there was a gain in futures price of soybean to as much as 40 cents in a few days time. The eventual decline in futures price was brought about by the lack of any damages to soybean that year. The impact on prices is basically determined by two forces. The bullish trend from speculative forces and the bearish trend from increased production and high stock to use ratio would eventually determine the level and volatility of soybean prices. In order to minimize the risk from these fluctuations, the farmer would need to combine good management practices with available market instruments. These include insurance and advanced financial markets such as futures hedging, forward contracts, call and put options etc. Historically, soybean futures have been traded on Chicago Board of Trade. Buying futures in soybean takes place when prices are expected to rise and selling takes place when they are expected to fall (See Schnepf et al. (1999) for a discussion of all available insurance and non-insurance options for corn and soybean growers).

Links to other Invasive Pests

The benefits of a real time tool for aiding farmers in decision making under threat from sbr cannot be overemphasized. The benefits may be even higher in the event of multiple pest infestation that have consequences for the same group of crops or farmers. For instance, the threat of avian flu influenza is a real one for the United States. The main carrier of this virus, chickens, is also the largest consumer amongst livestock of soybean products in the US. In 2000, soybean meal consumption by poultry amounted to about 44 percent of the total demand amongst the livestock. Arrival of avian flu would definitely impact demand for soybean, thereby having an impact on soybean prices. Having online software that reflects such impacts through hypothetical scenario analysis could greatly enhance farmers' preparedness against invasive pests.

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