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Farming as Feedback Control

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Abstract— **This paper surveys a brief history of agriculture, demonstrating how advances in genetics, equipment, and management practices have resulted in the remarkable productivity experienced by today's agriculture industrial complex. We then show that progress in each of these areas is, in part, the result of new solutions to a feedback-control problem, whether it be for selective breeding, exploiting new sensor and actuation technology on a tractor or harvester, or using advanced crop and weather models to make better decisions about irrigation or pesticides. The paper concludes with an invitation for the controls community to explore the varied and important feedback-control problems in this area, emphasizing that sustainably feeding the exponentially growing global population, without harming the environment, will demand creative, careful thinking for years to come.**

I. Introduction

The population of the world is growing, with estimates of a population of 9 billion by 2050, [53]. To support this growing population, the world will need to increase its food production by an estimated 50-70%. It is not likely that much new land will be converted to agricultural purposes to support this growth; instead, this growth will have to result from an increase of yield production from existing farms.

A large gap exists between achievable yields and actual yields obtained by farmers. In many regions, some farmers are able to negate this gap where neighboring farmers experience a significant gap during the same period. The existence of and variation in gaps is strong evidence that better management practices is capable of increasing yields globally [31].

Furthermore, agricultural activity is recognized to have a negative impact on the environment such as the introduction of water and air pollution by fertilizers and pesticides, the generation of waste products, and the acceleration of ground erosion [61].

In recent years, feedback and control practices have been used to minimize the gap between expected optimal yields and actual yields as well as minimizing the environmental impact of agricultural activity. Continued innovation will be required in order to responsibly meet the future demand for agricultural products.

II. A Brief History of Agriculture

In order to understand how to best prepare for the future, we begin by looking at agricultural change from the past. From prehistory to the present agricultural advancement has had a profound impact on humanity, often driving the technological, economic, and sociological changes that have resulted in our modern civilization. This section begins in the time of the industrial revolution and shows the basic trends and patterns that have led to the present agricultural needs and the potential of feedback and control to provide solutions to those needs.

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A. 1740 - 1840: British Agricultural Revolution

The British Agricultural Revolution, concurrent with the Industrial Revolution, was characterized by an increased productivity of the land as well as in yields that enabled the British community to feed a swiftly growing population. This increase in yields and productivity was made possible by new equipment, such as the seed drill, new management ideals, such as the introduction of crop rotation, and an improved understanding of genetics, which was applied to areas such as livestock breeding [59].

B. 1840 - 1940: First American Agricultural Revolution

As the influence of the Industrial Revolution expanded from Britain into the Americas, the United States began to experience its own agricultural revolution. This revolution is characterized by a shift from human-powered agriculture to animal-powered machinery leading to higher productivity per farmer. Many animal-powered machines were introduced, perfected, and patented between 1830 and 1860, including mechanical reapers, seed drills, corn cultivators, threshing machines, mowing machines, hay rakes, wire benders, and combines [48], [49], [40].

C. 1940 - 1990: Second American Agricultural Revolution

Starting in the last quarter of the 19th century, Farmers became agitated with the low prices of crops making profits difficult to obtain. By the 1930s, the situation almost precipitated an armed revolt by the farmers. Responding to this and other economic pressures, the United States government passed the New Deal, which included legislation where the government committed to buying up surpluses, providing price supports, paying farmers to leave field fallow, and bringing electricity, water, and education to the farmers [49]. Then the United States entered World War II, which caused a sharp rise in the demand for and the price of farm products. This demand did not fall after the war due to foreign relief efforts [48].

This new and favorable economic climate fueled the Second American Agricultural Revolution, characterized by an increased productivity per farmer and an increased yield per acre. These increases were the result of widespread mechanization of farm equipment, lower prices and greater

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utilization of lime and fertilizer, increased implementation of no-till farming and other soil conservation practices, use of improved genetic varieties of crops and livestock, and more effective control of weeds, insects, and disease [48].

D. 1990 - Future: Third American Agricultural Revolution

Both the First and Second American Agricultural Revolutions occurred because (a) farmers worked in a favorable political climate, and (b) technology was created allowing the increase in productivity and/or yield of an acre of land.

Today, we are seeing the beginnings of a third agricultural revolution. With the rise in population and grain prices, the agriculture industry is yet again in a favorable economic environment. Furthermore, we have seen the introduction of new technologies. New hybrids, fertilizers, and chemicals can significantly increase the yield and minimize the risk of external disturbances, such as weather, pests or weeds.

This current revolution is an opportunity for systems and controls researchers to design and implement interesting solutions to aid the improvement of yield and productivity in agriculture, while not compromising sustainability or the environment.

III. Farming as a Feedback-Control Problem

As shown in Figure 1, the entire process of farming can be viewed as a feedback-control problem, with several smaller feedback-control problems embedded within. Taking a broad view of the farming process, the plant we are trying to control encompasses an entire farm or a specific management zone within a farm. Uncertainty in the plant comes in the form of unpredictable forces, such as weather or pests, which can affect the farm both positively and negatively.

The farm's progress is monitored by sensors that collect data–such as yield data or nitrogen levels–and that data is interpreted and evaluated before management decisions are implemented. The management decision a farmer makes for his management zones are the control laws of the feedback-control loop. In addition, external financial factors such as government subsidies, insurance, and market prices affect the overall management decisions. These decisions are then instituted across the various management zones by several actuators, such as vehicles that disperse pesticide, which affects the state of the farm.

A. The Plant

The characteristics of a farm or management zone are governed heavily by its location. The location of a farm determines the weather and climate of the zone along with soil that forms there. This in turn affects the possible seeds that can be grown within the zone and what genetic enhancements need to be made in order for a crop or livestock to thrive.

1) Location of Farm: Climate parameters that influence both crop growth and livestock yields, such as solar radiation, average precipitation, air temperature, and humidity differ from country-to-country, from state-to-state, and from farm-to-farm because of the various nuances associated with the location. Whether it be the latitude of the farm or the elevation with respect to sea level, the location of a farm contributes to the type of climate and weather that is natural for that region as well as the soil types that have developed there [29].

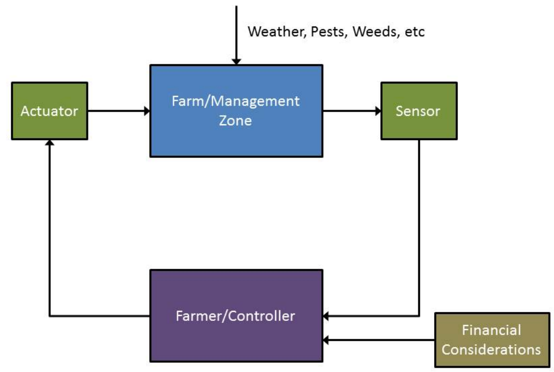

Fig. 1. Farming as a Feedback-Control Problem

Understanding the soil composition of the management zone is integral to understanding what management decisions are viable for the farm. The color of the soil is an indicator of the amount of organic matter available, while the texture of the soil affects factors such as water-holding capacity, water movement, soil micro-organisms, root growth and soil temperature dynamics [4].

2) Plant and Livestock Genetics: Although the idea of cross-breeding had been around for thousands of years, at the turn of the 20th century Mendelian inheritance introduced a universal theory formalizing how traits in an offspring could be predicted from traits in the parents, which improved the selective breeding process [35].

In the last few decades, genetic engineering has arisen as a method to improve animal and crop productivity. Genetic modification directly manipulates an organism's genome, which raises some interesting ethical questions [14]. These genetic modifications lend themselves to some interesting feedback-control problems. For example, mutations in pathogens increase the immunity of certain strains of diseases or new diseases are introduced that affect crops, which requires new herbicides to be created and dispersed in plants for the next season of growth [47].

B. External Disturbances

Beyond the inherent characteristics of the farm or management zone, external disturbances also affects crop growth, creating uncertainties in predicted crop yields.

1) Weather: Edward Lorenz, a pioneer in chaos theory, showed that weather is "intrinsically unpredictable for all practical purposes." Climate, on the other hand, is reasonably well defined. Extreme shifts from one day to the next do not occur naturally; therefore, there exists some level of predictability of the weather on a macro-level [26].

Variation in rainfall, especially in locations where irrigation is infeasible, can lead to vast variations in crop yield [3]. It is unfortunate that an inability to accurately predict rainfall persists, as made evident by the droughts in 2012, which drove crop yields down across the US [19], [44]. When the uncertainties due to rainfall are better understood, the risks of drought can be mitigated and controlled through the proper utilization of drought-resistant hybrids (see section III-A.2) or through the use of irrigation (see section III-E.2).

2) Pests: A farm needs to be constantly monitored so that pests in crops or diseases in livestock can be identified. Most insects, weeds, and diseases can be discovered fairly easily using a variety of different sensors and sensing techniques (see Section III-C). To combat against the threat of pests within a management zone, farmer must decide if an increased dose of herbicide or insecticide in a given management zone is necessary or if the situation requires the development of new chemical treatments via genetic engineering, as mentioned in Section III-A.2.

Although the identifying the existence of pests is relatively trivial, the prediction of the emergence of pests is a nontrivial problem. Researchers have been attempting for decades to understand the complex system associated with pest-crop models [34]. Although many models for predicting the presence and magnitude of pests over time have been developed, the unfortunate fact is that field-specific pest conditions are difficult to predict because of the number of factors involved [30].

C. Sensors

Given the various characteristics of the farm along with the effects of external disturbances there is much need for sensors and sensor networks in an agricultural management zone to collect data in order to make informed management decisions. With a plethora of sensors available for agricultural use, we focus on only a few related to crop growth.

1) Before Crop Planting: Soil Electrical Conductivity: Soil electrical conductivity has been shown to have a positive correlation with many soil parameters that are predictive of crop yield. There are two methods for determining soil electrical conductivity; the first uses a contact sensor, which are usually large and can be attached to the back of a farm vehicle, such as a truck [28]. The second method utilizes non-contact sensors, which work on the principle of electromagnetic induction. They are fairly small, making it easy for a single individual to carry them around in small management zones and testbeds [28].

2) After Crop Planting: Remote Sensing: Remote sensing ranges from placing sensors across fields that map weeds to flying over fields to capture aerial photographs that are useful for computer vision [41]. The data collected via remote sensing can then be used to identify pest infestations, water deficiencies, nutrient deficiencies, or the overall quality of the crop, thus allowing for updated management decisions [56], [57]. For example, low cost multi-spectral systems utilize airborne digital and video camera technology to capture high resolution images capable of identifying weeds. [36].

Remote sensing has also been successful in determining nitrogen need in corn, allowing for management decisions to focus on nitrogen-starved areas of the corn field [52], [60]. In some cases remote sensing can be combined with crop simulation models for iterative adjustments of model parameters, such as initial conditions or cultivar parameters to improve model accuracy through feedback-control [46].

3) After Crop Harvest: Stalk Nitrate Test: The stalk nitrate test or “end-of-season cornstalk test” is useful in determining the nitrogen needs of a corn crop during the season. The basic principle is that the lower stalks are drained of nitrogen during the grain-filling period if the soil is nitrogen-starved, while crops with high nitrogen concentrations in the lower stalks may have nitrogen excess. Dependent on the result of the test, management practices can take into account which management zones appear to have nitrogen starvation and which may have excess nitrogen, so fertilization practices can be adjusted accordingly [11].

D. Actuators

As with sensors, there are many different actuators available for use on an agricultural management zone, though only a few will be discussed here. We will focus on how certain technologies aid farming vehicles, which are the primary form of actuation on a farm.

1) Global Positioning Systems: The prevalence of patents [20], [37], alongside a plethora of papers [10], [9], [43], attest to the fact that GPS has been extremely beneficial in solving the problem of guiding farm vehicles. The basic implementation of feedback-control for farming vehicles using GPS services is that the location of the vehicle is continuously fed to the controller, which in turn updates the steering of the vehicle, guiding it towards a new location.

Some researchers have made progress in improving guidance systems on farm vehicles thanks to improvements in technology such as the Carrier Phase Differential GPS, which is an inexpensive GPS receiver that can measure a vehicle’s position to within a few centimeters and a vehicle’s heading to within 0.1° [9]. Other researchers have used tools from controls, such as Kalman filters for state estimation, in order to insure against the shortcomings in GPS technology and maintain continuous guidance of the farm vehicle [10], [62].

2) Computer Vision: The use of computer vision is amenable to that of feedback-control, since computer vision systems often receive continuous input until an object is recognized and then the controller determines the appropriate action.

For example, machine vision has been used to distinguish crop rows from furrows or to distinguish crops from weeds [5], [58]. Machine vision has also been used for improving the guidance of farming vehicles in applications where GPS performed poorly such as a citrus grove where the tree canopy blocked satellite signals to the GPS receiver [55] or where the vehicles were required to avoid objects within the field [6].

3) Variable Rate Technology: A feedback-control system exists which uses sensors and actuators to control droplet size and application rate for agricultural chemicals [41]. Currently, off-line approaches, which require one operation for data collection which is then processed before a separate operation occurs for implementation, are popular due to higher accuracy. However, farmers are likely to switch to on-line systems as real-time sensing technologies become more mature, allowing for collection, processing and implementation of variable rate technology in a single operation, greatly improving efficiency [56], [21].

4) Multi-Vehicle Control: The efficiency of farming equipment can be greatly enhanced if an entire fleet of vehicles is automated. Work in this direction has been focused on developing interfaces allowing users to easily control several semi-autonomous vehicles simultaneously [16], on planning routes allowing the fleet to most efficiently cover an entire field [15], and developing coordination, scheduling, and optimization algorithms to most efficiently allocate and execute tasks among the fleet [25].

E. Feedback-Control Laws: Management Decisions

Once sensors have collected data, it then needs to be processed and then understood to a point where management decisions, i.e. feedback-control laws, can be made. These management decisions can then be implemented on the farm by various actuators.

Although farmers have been making management decisions for thousands of years, new technology is allowing them to improve their decision making process in order to increase crop yield or animal productivity. The ideology of utilizing modern technology to aid in decision making in agriculture is known as precision farming, [41].

Sadly, the lack of formal research into Decision Support Systems (DSS) is hindering the adoption of precision farming [39]. Further work in the controls community will be needed to develop the precision-farming technology necessary to improve efficiency, without compromising sustainability or the environment.

In this section we focus on some of the major management decisions that farmers are required to make in order to maintain their farm and increase yields.

1) Fertilizer: One of the most important management decisions available to farmers to increase the yields of crops is the application of fertilizer [45]. In the nineteenth century, artificial fertilizers, especially nitrogen, were low in supply and therefore an expensive and impractical method to increasing the yield of a farm. However, in the 1930s, the Haber-Bosch process was perfected, allowing for the relatively-cheap manufacture of usable ammonia from hydrogen and nitrogen [38].

With the sharp decline in the price of nitrogen, farmers began applying large amounts of fertilizer to their fields, resulting in an increase in yields that is, in part, responsible for the Second American Agricultural Revolution [48], [49] and the tripling of global food production in the last 50 years [42]. Today, approximately 97% of all planted corn acres in the United States receives some sort of nitrogen treatment [50].

Over the last century, nitrogen has been cheap enough that farmers in developed countries have applied much more nitrogen than is necessary to maximize yields or profits in order to mitigate the risk of nitrogen starvation and low yields [32]. However, due to the rapidly increasing price of nitrogen [2], such a strategy is no longer economical for farmers in developed countries, much less in developing countries [60], [32]. Furthermore, the over-application of nitrogen has been shown to have a significantly negative impact on the environment. For example, nitrogen in fertilizer applied to corn in the U.S. Midwest is exported to the Gulf of Mexico via the Mississippi and Atchafalaya rivers, becoming the leading source of seasonal hypoxia in the region [23].

To mitigate the environmental impact of over-application, the USDA has issued a set of nitrogen best management practices (BMPs). These BMPs focus on controlling the rate, timing and method of fertilizer application [50]. Though better at preserving the environment than conventional practices [22], the BMPs are largely ignored by a majority of farmers [50]. More work by the controls community is necessary in order to make a truly economical and environmentally-friendly fertilizer application practice.

2) Irrigation: Irrigation is a mechanism whereby the farmer can provide moisture and precipitation to the crop when the weather does not. Since water affects both the yield of the crop as well as the movement of nitrogen and other nutrients in the soil, irrigation management is a critical aspect of an effective management practice [24].

In regions where natural precipitation cannot fully meet the needs of the crop and where the water supply for irrigation is short, the practice of limited irrigation is often used. This practice seeks to maximize the productivity of the limited supply of water by timing the irrigation applications at critical crop growth stages [8].

In regions where natural precipitation typically provides enough rainfall to fully supply the needs of a crop, irrigation can be used to mitigate the risk of potential droughts during the critical periods when the crop most needs water [13].

Recent research into irrigation scheduling has shown that farmers tend to use heuristics rules to trigger irrigation usage, which could lead to poor performance due to a lack of operational constraints, though model predictive control can be used to account for these operational constraints [51].

3) Crop Rotation: Farmers engage in the practice of crop rotation by growing different types of crops within the same field or management zone in sequential seasons. In the 1960s and 70s, scientists felt that the use of crop rotation would become obsolete with the increased use of synthetic fertilizers and pesticides. However, evidence has shown that, even today, crop rotation can increase yields and profits and allow for a sustained production in a field. For example, it has been shown that when maize is in a 2-year rotation schedule with soybeans, fields tend to yield 5-20% greater yield than in fields that plant maize continuously. Caution must be used, however, since short rotation cycles have also been shown to cause a degradation in yield [18].

F. Finance: Effects on Management Decisions

As described in Section III, management decisions aren't based wholly on the performance of the farm. Figure 1 shows that there are various external forces that do not directly affect the animals or crops on a farm, but still have an influence over management decisions.

1) Market Prices: Due to the growing global population as well as an increased use of alternative bioproducts such as ethanol and other biofuels, the demand for crops and livestock is increasing. At the same time, the increase in productivity is slowing. These factors combined have led to an increase in prices of agricultural products, a trend expected to continue in a long-run [31], [1]. To date, this increase in prices has led to an increase in farmers' profits, allowing farmers to invest in the yield-enhancing and labor-reducing technologies necessary to meet this rise in demand [12].

2) Government Subsidies: As described in section II-C, the New Deal in the United States provided the economic foundation for the growth experienced in the Second American Agricultural Revolution. Government subsidies of farmers was one of the components of that policy and has persisted to this day. On average, the US government spends over $17 billion annually, an average of $7000 per farmer, in agricultural subsidies, thus providing some economic freedom to farmers [33].

Due to the complex nature of the agriculture economic environment introduced by subsidies, a change in subsidy policy can have a profound impact on the status of the entire industry. Work has been directed to evaluating the nature of subsidies within the EU, determining that the subsidies amount to some two-third of agriculture's gross-value added within the EU. This work used the AgriPoliS model to run simulations in order to determine safe methods to reduce the levels of these subsidies while avoiding significant harm to the industry [7]. Further work in this direction can help inform methods to safely incentivize growth in the agricultural industry.

3) Agricultural Insurance: Agricultural insurance manages risk for farmers, allowing for stable farming income while promoting investment in agricultural pursuits. Agricultural insurance manages risk ranging from financial considerations (fluctuations in interest rates and foreign exchange rates), market considerations (supply vs. demand), as well as natural risks (inclement weather, such as drought or early onset of winter) among others [17]. Agricultural insurance requires continual monitoring of a farm to ensure that the system is not abused and to stop fraudulent claims [27].

The development of agricultural insurance policies relies on the ability of an insurer to accurately estimate risk and ensure that the policy is not susceptible to abuse. The biggest issue associated with agricultural insurance is the role of asymmetric information, which occurs because the insurer knows very little about a particular farmer's farming practices while the farmer knows every detail about his own management decisions. Asymmetric information can lead to adverse selection, a situation where information hidden from the insurer can lead the insurer to make non-optimal decisions. To protect against adverse selection, the insurer typically uses an ad-hoc approach to minimize risk. Other than constant monitoring, it is currently difficult for the insurer to minimize the risk associated with moral hazard [54].

IV. Conclusion

Agriculture has played a critical role in the growth and development of civilizations throughout history. In recent centuries, a rapid growth in technology has created several agricultural revolutions marked by sharp increases in crop yields per acre coupled with a sharp decline in the amount of labor required to produce this yield.

In order to sustain a growing population, these trends of increased yield and decreased labor requirements will need to continue. To support these efforts, new technology has been introduced to agriculture such as improved crop and livestock genetics, finer sensing and actuation technologies, the development of more effective management practices, and a profitable agricultural market enabling farmers to invest in these technologies.

Feedback and control is the unifying technology that will enable a continued efficiency and automation on farms. However, further thought and work in this field are critical in order to generate the yields and productivity necessary to sustainably support our future population without further damaging the environment.

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