Stochastic Optimization Model Using Remote Sensing Technologies for Agricultural Management in Africa

Wesonga Ronald

Makerere University, Institute of Statistics and Applied Economics, Department of Planning and Applied Statistics

P.O. Box 7062

Kampala, Uganda

E-mail: wesonga@isae.mak.ac.ug

Phone: +256-772-454680

Abstract

Information communication technology is the key to agricultural development if least developed countries (LDCs) are to optimize agricultural management (Di Bella, 2004). Many systems have been developed that collect vast amount of vital electronic data, perform data analysis and disseminate information. However, due to limited accessibility to these ICTs, LDCs still lag behind in exploiting technologies for timely decision making in agricultural management (Elisabetta Carfagna, 2005).

Agricultural management in Africa is hampered by among other parameters the uncertainties that surround the following questions: when is the next rainy season? How long are the next rains expected to take? What is the likely intensity of these rains? Are they sustainable? What if we planted now? Are we likely to gain if we waited for two more months? How do we determine the disease or pest attaching our plants? How about if we used the other chemical/fertilizer?

Although remote sensing technologies are not popularly used in Africa, in this paper we explore available advanced remote sensing technology that can be exploited to the advantage of agricultural sustainability and modernization in Africa region.

We also develop and present a model that attempts to minimize the common phenomenon in LDCs of time wastage before planting of crops, hence optimization of agricultural management in Africa. The model developed here shall be an important decision making tool for any agricultural manager based at a given farm and accessing remote sensing technologies such as satellite data.

We recommend the use of remote sensing data for use in obtaining the best results from the optimization model presented in this paper.

Key words: ICT, stochastic optimization model, agricultural management, remote sensing, MSG satellite, Africa

Introduction

Satellite imagery and related information and communication technology is one of the most important avenues of information and knowledge discovery, an aid to making timely and informed decisions in agricultural production in the world. People have long been interested in extracting immediate value today from agriculture and forests, while preserving their characteristics for future generations. During the seventeenth century in England, for example, the fundamental interests of the realm; prosperity, security, and liberty, were invoked to support the positions of both conservationists and developers (Schama, 1995: p. 153): "The greenwood was a useful fantasy; the English forest was serious business." In the century just past, the discussion has remote sensing as an information source (Lefsky et al., 1999a). It is not possible to consider all of these remote sensing devices in the world, but some are introduced in this paper and briefly discussed.

The Meteosat Second Generation spacecraft was designed to take advantage of new technologies and to improve on the already successful and proven spacecraft design of the original Meteosat satellites. The SEVIRI radiometer on-board the MSG satellite has a total of 12 channels that scan images of the earth every 15 minutes (Project, 2004).

The High Resolution Visible channel provides data at 1km sampling, the other channels sample at 3 km. In addition to the main SEVIRI payload the satellite carries an instrument for the measurement of terrestrial radiation (Geostationary Earth Radiation Budget - GERB) telecommunications equipment for the dissemination of processed imagery and products, as well as, components for the reception and relay of distress messages for search and rescue (GEOSAR) (Campbell, 2006; Lillesand, 2004; Richardson Clarence, 2004).

Agricultural Management in Africa

Africa is one of the largest continents in the world with over 70% of its inhabitants practicing agriculture production most of which is subsistence. Agriculture is undoubtedly the most important sector in the economies of most non-oil exporting African countries. It constitutes approximately 30% of Africa's GDP and contributes about 50% of the total export value, with 70% of the continent's population depending on the sector for their livelihood. Production is subsistence in nature with a high dependence on the rain. The debate on climate change and its impacts on agriculture is therefore very crucial to the very survival of the continent and its people. The continent is particularly susceptible to climate change because it includes some of the world's poorest nations (Elisabetta Carfagna, 2005; Van Niel, 2004).

(Esteve Corbera, 2006) in their report state that, the climate in Africa is predominantly tropical in nature, which is broadly classified into three main climatic zones: humid equatorial, dry, and humid temperate. Within these zones, altitude and other localized variables also produce distinctive regional climates. The climate also varies cyclically over periods of decades, centuries, and millennia as well as from year to year. Climate change, especially indicated by prolonged drought is one of the most serious climatic hazards affecting the agricultural sector of

the continent. As most of the agriculture activities in African countries hinges on rain fed, any adverse changes in the climate would likely have a devastating effect on the sector in the region, and the livelihood of the majority of the population.

Though changes in the climate may affect the whole continent, its distribution may vary across the continent. Climate change in the already arid northern sub-region of the continent is expected to enhance desertification and bring a gradual decrease in forest cover and arable land. In the Sahara and Sahel sub-regions, rainfall is predicted to drop, resulting in soil degradation and an increasing number of dust storms. In northeast Africa, more intense dry periods and shorter wet seasons are expected to affect even huge river systems such as the Blue Nile, leading to serious water shortages and adverse consequences for the agriculture and forestry sectors throughout the region. East and Central Africa will also see its agricultural capacity decline. In West Africa, more frequent and longer dry periods are expected, again threatening crop failures. Coastal areas may also be affected by rising sea levels and intrusion of salt water into inland freshwater resources. Southern Africa also faces similar threats. The staple food for the region, maize, is particularly susceptible to drought. Wetlands of international importance and wildlife are also under threat from drought in Southern Africa. Climate change, therefore, is expected to worsen the food supply, hence, exacerbate the widespread poverty in the region.

(Mike Hulme, 2000) discussed the five main climate change related drivers: temperature, precipitation, sea level rise, atmospheric carbon dioxide content and incidence of extreme events and showed how they may affect the agriculture sector in the following ways:

- Reduction in crop yields and agriculture productivity: There is growing evidence that in the tropics and subtropics, where crops have reached their maximum tolerance, crop yields are likely to decrease due to an increase in the temperature.
- Increased incidence of pest attacks: An increase in temperature is also likely to be conducive for a proliferation of pests that are detrimental to crop production.
- Limit the availability of water: It is expected that the availability of water in most parts of Africa would decrease as a result of climate change. Particularly, there will be a severe down trend in the rainfall in Southern African countries and in the dry areas of countries around Mediterranean Sea.
- Exacerbation of drought periods: An increase in temperature and a change in the climate throughout the continent are predicted to cause recurrent droughts in most of the region.
- Reduction in soil fertility. An increase in temperature is likely to reduce soil moisture, moisture storage capacity and the quality of the soil, which are vital nutrient for agricultural crops.
- Low livestock productivity and high production cost: Climate change will affect livestock productivity directly by influencing the balance between heat dissipation and heat production and indirectly through its effect on the availability of feed and fodder.
- Availability of human resource: Climate change is likely to cause the manifestation of vector and vector born diseases, where an increase in temperature and humidity will

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create ideal conditions for malaria, sleeping sickness and other infectious diseases that will directly affect the availability of human resources for the agriculture sector.

The impact of these adverse climate changes on agriculture is exacerbated in Africa by the lack of adapting strategies, which are increasingly limited due to the lack of institutional, economic and financial capacity to support such actions plus limited ICT usage for the monitoring such as remote sensing technologies. .

Africa's vulnerability to climate change and its inability to adapt to these changes may be devastating to the agriculture sector, the main source of livelihood to the majority of the population. The utmost concern should therefore be a better understanding of the potential impact of the current and projected climate changes on African agriculture and to identify ways and means to adapt and mitigate its detrimental impact.

Climate Change and Agricultural Management in Africa

(Chalmers, 2007) argued that analysis of the impacts of climate change suggests that agro-ecological systems are the most vulnerable sectors. Agriculture in low latitude developing countries is expected to be especially vulnerable because climates of many of these countries are already too hot. Further warming is consequently expected to reduce crop productivity adversely. These effects are exacerbated by the fact that agriculture and agro-ecological systems are especially prominent in the economies of African countries and the systems tend to be less capital and technology intensive. Predictions of impacts across regions consequently suggest large changes in the agricultural systems of low latitude mostly, developing countries.

Using Remote Sensing technology in Agricultural Management in Africa

According to (Schowengerdt, 2006), remote sensing refers to the activity of using electromagnetic properties to view or interpret phenomena while not physically in contact with it. Examples of remote sensing range from taking pictures with your digital camera to using radar to find planes in the sky to analyzing satellite imagery to find water on Mars (Kyllo, 2003). Quite often, use of these technologies has many applications in the developed countries among which are data collection for defensive use. However, these remote sensing technologies can equally be useful in the developing countries which mainly rely on agriculture for survival, yet cannot maximize agricultural production because of lack of sufficient data for proper planning of agricultural management(Moazenpour, 2006; Sergio M. Vicente-Serrano, 2006).

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Eumetsat Satellite Applications Facilities

The Meteorological Transition in Africa (MTA) project set up by Eumetsat assists a network of 53 countries and four regional centers in Africa with equipment, training and application support to obtain and use remote sensing data for a multitude of purposes(Taube, 2004) .

With the use of their new MSG satellite, data is made accessible through this project. African National Meteorological Services, in close partnership with others involved with development in Africa, and in addition to the traditional meteorological services, develop applications in the following fields: Water Development and Management, Flood Forecasting and Monitoring, Flood Damage Assessment, Agricultural Management, Landslide Risk Monitoring, Food Security, Post Crisis Food Aid Assessment, Forest Fire Monitoring, Forest Fire Risk Assessment, Land Cover Changes and Pest Monitoring (Project, 2004). All of these fields are necessary parameters in the management of agricultural production.

The Vegetation for Africa, **VGT4AFRICA** project that began in March 2007, also disseminates via EUMETCast the following products to all reception stations in Africa. This project uses the ICTs developed and maintained by Meteorological Transition in Africa. These products were selected by representatives from the PUMA network. Products delivered by the VGT4AFRICA partners include: NDWI-water index, burnt area, phenology, small water bodies, albedo, fcover and LAI (Taube, 2004).

Drought Monitoring using MSG Satellite data

According to (Elisabetta Carfagna, 2005), desertification is not the natural expansion of existing deserts but the degradation of land in arid, semi-arid and dry sub-humid areas due to human activities and climatic variations. It is one of the most alarming processes connected to soil productivity loss and the thinning out of the vegetative cover. Over 250 million people are directly affected by desertification and over 4 billion hectares of land are at stake in the world most of which are in LDCs. The UN estimates that each year desertification and drought cause an estimated $ 42 billion in lost agricultural production.

The EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA SAF) led by the Portuguese National Meteorological Service, has been used to monitor desertification and drought threatened areas, providing an important source of information to combat environmental degradation. The information is also vital for many other activities such as agriculture, forestry and terrestrial transport safety management (Elisabetta Carfagna, 2005).

The Land SAF uses operational data from EUMETSAT's geostationary satellites, Meteosat as well as Metop-A its first polar orbiting satellite, to increase the usage of data over land, land-atmosphere interactions and biospheric applications; products include Land Surface Temperature, Surface Albedo, Snow Cover and Down-welling Surface Long- and Short-wave Fluxes (Elisabetta Carfagna, 2005). New developments are Vegetation Parameters, Soil Moisture and Evapotranspiration. The operational Land SAF products are available free of

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charge in near real time via EUMETCast – EUMETSAT's Broadcast System for Environmental Data that is accessible to Africa.

Stochastic Optimization Modeling of Agricultural Production in Africa

Some attempts have been made to develop models for agricultural production. (Kiniry, 2006), developed a general agricultural and ecosystem simulation models valuable for technology transfer that require a realistic, process-oriented plant model that can be easily applied to different crops, grasses, and woody species. (David A. Stainforth 2007), discussed in detail some issues in the interpretation of climate model ensembles to inform decisions. The model developed in this paper seeks to help decision making by obtaining an optimal situation to minimize unnecessary delays in agricultural production using stochastic modeling (Barry, 2003). Decisions made in agricultural production depend on a number of parameters including the stochastic weather conditions which also resolve a number of things among which are the planting and harvesting periods, besides whether or not a crop will successfully grow within a predetermined time period. Remote sensing will aid a farmer in such a way that the number of scenarios faced by a farmer in a given year is minimized. It will be possible for the farmer to have continuous uninterruptible year to year agricultural activities given that ICTs such as remote sensing technologies are used.

Objective Function for the Model

Minimize the expected sum of inter-seasonal crop planting delays.

$$Min \sum_{q \in \Theta} P\{q\} x \left\{ \left[\sum_{c \in \Phi} \sum_{t=Plantc}^{T+1} (t - Plantc) x \left(X_{c,t}^q - X_{c,t-1}^q \right) \right] + \lambda \times \sum_{t=1}^{T} W_t^q \right\}$$

Constraints

$$t \in \{Plantc, \ldots, T+1\}$$

$$X_{c,t}^q - X_{c,t-1}^q \geq 0 \qquad \text{for all} \quad c \in \Phi$$

$$\mathbf{q} \in \Theta$$

$$W_{t-1}^q - W_t^q + \sum_{c \in \Phi} \left(X_{c,t}^q - X_{c,t-1}^q \right) \leq M_t^q \quad \text{for all} \quad \begin{array}{l} t \in \{1, \ldots, T+1\} \\ q \in \Theta \end{array}$$

$$W_0^q = W_{T+1}^q = 0$$

$$X_{c,T+1}^q = 1$$

Notation definitions

Let

$\Phi = \{1, 2, \ldots, C\}$ be a set of crops

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$\Gamma = \{1,2,....,T+1\}$ be a set of finite time periods, seasons

Given crop $c \in \Phi$ then $Plant_c \in \Gamma$ and $Harvest_c \in \Gamma$

Let $\lambda \geq 1$ where λ the unit cost is for dry season and rainy assumed for all crops

Let Θ be a set of capacity scenarios where $q \in \Theta$ and

P{q} be the unconditional probability of occurrence of a scenario $q \in \Theta$

M_t^q be scenario-specific time varying capacity of the farm where $t \in \Gamma$ and $q \in \Theta$ which set upper bounds on the number of crops that can be grown during each time period

M_{T+1}^q is the farm capacity of the last time period

Model variables

M is the total number of branches of the scenario tree $M \geq |\Theta|$

N_i is the number of scenarios corresponding to the ith branch, where $i \in \{1,2,...,M\}$

$\Omega_i = \{S_1^i, S_2^i,..., S_k^i,..., S_{N_i}^i\}$ is a set of scenarios corresponding to branch i and $S_k^i \in \Theta$

O_i is the start node time period of a branch

μ_i is end node time period of a scenario tree branch

Decision variables

$X_{c,t}^q = \begin{cases} 1 \ if \text{ crop c is planned to be ready by end of time period t under scenario q} \\ 0 \text{ otherwise} \end{cases}$

where

$q \in \Theta$
$c \in \Phi$
$t \in \{Plant_c,....,T+1\}$

Auxiliary variables

W_t^q is number of crops planned at the end of time period t under scenario q

Assumptions

- System – field/farm is empty(no crops) at the beginning of the planning period
- All crops grow and are harvested by the end of period T+1

Discussion

Production delay of crops in Africa is a function of the time period amongst other parameters. Some time periods are more favored with the necessary optimal weather and resource facilitation than other time periods. Quite often the weather parameter is stochastic in nature and tends to vary in unpredictable way such that for the majority of peasant famers in Africa, a whole season or more may go without any agricultural production. These delays are actually a source of food insecurity and hunger in Africa as whole despite the vast amount of productive land. The question of how to minimize agricultural production delays for crops was the major concern of this paper. It was shown that the decision making mechanism for any farmer in Africa is cyclic and met by a number of decision points. These decision points lack the necessary data for most farmers and hence resulting into low food and agricultural production on the continent. With the availability of such models as one developed and presented in this paper and the remote sensing data from the meteosat second generation satellite, it is highly probable that the first millennium development goal of reducing hunger and poverty in Africa will be met with sufficient smiles.

Conclusion and Recommendations

In order to maintain a constant and sustainable agricultural production, one requires perfect knowledge of a number of parameters necessary for agricultural production that may be possible with use of the available remote sensing technologies such Meteosat Second Generation satellite data. MDG 1 is to eradicate poverty and hunger with two targets thus; halve between 1990 and 2015 the proportion of people whose income is less than one dollar per day and halve between 1990 and 2015 the proportion of people who suffer from hunger. Achieving these targets requires a lot more efforts than what is currently exerted. Therefore, the need to use tools such as stochastic optimization models developed in this paper. Specifically, the paper observes that to minimize the cost of production while maintaining agricultural production throughout the year, λ, the cost ratio of production between dry and wet season should be kept as close to one as possible.

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