Chapter 1

Introduction

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Chapter 1

Introduction

1.1 Food Security: A Global Concern

Today, there is no doubt about the fact that the population of the world as well as that of India is continuously increasing (Figure 1.1). This leads to an increase in the demand for food, clothing, housing and other human needs. The world population is further expected to grow to 9.1 billion by 2050 (FAO-HLEF, 2009). Food security of the ever increasing population is a real challenge to the world governments. There is no other way to deal with this challenge but to produce more food grains and manage it optimally. To produce more food grains, either the productivity of food crops or the area under food crops needs to be increased. The other way is to increase both simultaneously and optimally. As far as productivity is concerned, it depends on a number of land and weather parameters and their complex interplay. Then each crop has a limit to which the productivity can be increased, called Potential Crop Yield. The prevailing conditions of environment and the lack of availability of resources make it extremely difficult to achieve the potential productivity. Hence, continuous efforts are being made to explore different ways to achieve the potential crop productivity in a sustainable manner. As far as the crop area is concerned, availability of overall land is also limited. Increasing the land under crops leads to a decrease in the land under some other land cover / land use class. No land cover can be altered or changed easily, without affecting adversely. Each and every type of land cover has its own importance in the global ecological balance. For the last five decades, the overall production and consumption of food grains on global scale is increasing (Figure 1.1). A projection of food requirement by 2050 suggests that the increase in production alone will not be sufficient to ensure food security for everyone (FAO-HLEF, 2009). Moreover, the demand of the ever increasing population needs more land to meet the increased requirements of housing, clothing, and entertainment. The global crop area and production statistics show that both the overall production as well as utilization of the crops are continuously increasing (FAO, 2015a; FAO 2015b). A good thing is that the food grain stocks are also increasing, which is needed in case of any natural calamity or any unforeseen disaster. These increasing trends in production, utilization, and stocks of total cereals along with the trends in production and acreage of wheat at the global levels are shown in Figure 1.2. The left chart shows temporal estimates for the global cereal while the right chart shows global wheat estimates from 2006 to 2015. Nonetheless, Pingali (1999) mentions that there is some evidence that in the most intensively cultivated areas, particularly those with double or triple cereal rotation, resource base limitations may now be leading to a slackening productivity growth.

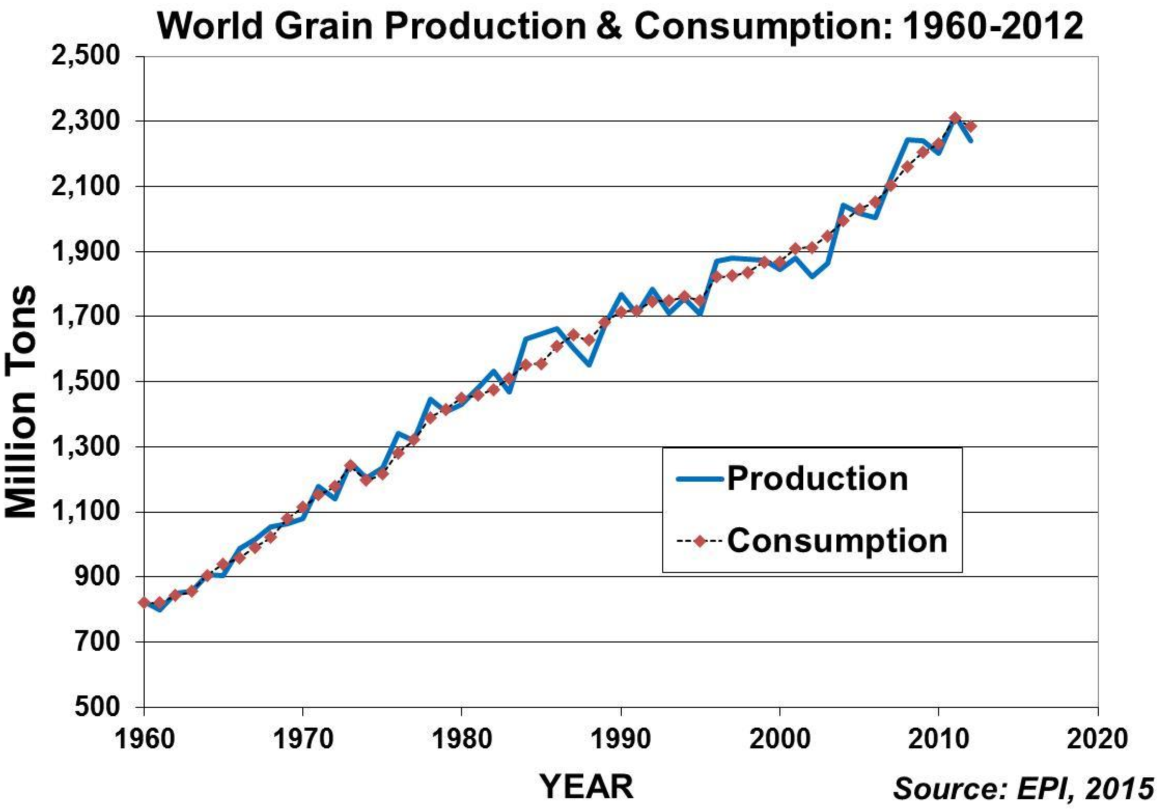
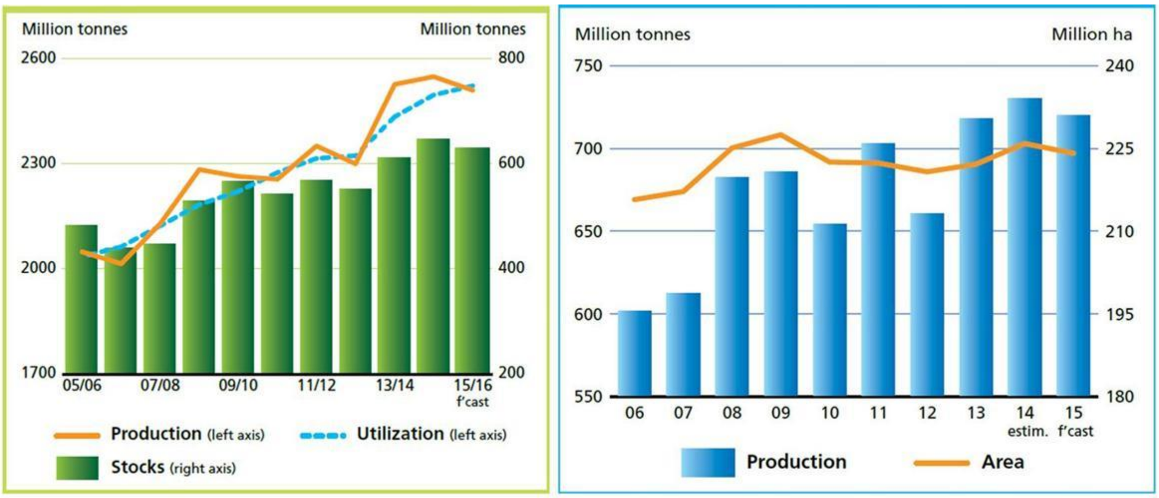


Figure 1.1. Global Food Grains Production and Consumption.

Natural calamities like droughts, floods, crop diseases, hail storms, wind storms are known to adversely affect the crop production. As per the findings of FAO – UN, the agriculture sector absorbs approximately 22 percent of the economic impact caused by medium- and large scale natural hazards and disasters in developing countries (FAO, 2015c). Way back in 1950s, in India a series of natural calamities affected the grain production and threatened some regions with famine. To offset serious crop losses more than 6 million tons of cereals were imported. The food scarcity was aroused not merely due to a temporary disequilibrium between demand

and supply, but also because of the growing pressure of population (FAO, 1951). Changing climate further increases the pressure on the already stressed natural resources. Recently, The United Nations has urged world governments, aid organizations and the private sectors for a stronger response to the devastating impact caused by the El Niño climate event on food security, livelihoods, nutrition and health of some 60 million people around the world (FAO-UN, 2016).



Global cereal data Source: FAO, 2015a Global wheat data

Figure 1.2. Global Cereals and Wheat Statistics for Last 10 Years.

Programs and policies are being developed to provide a higher-technological assistance and greater capacity to the countries for tackling climate change. A forward looking agreement of a 3-year partnership and a strategic alliance took place between Google Maps and the FAO to work closely together and make geospatial tracking and mapping products more accessible to experts involved in developing forest and land-use policies (FAO-Google, 2016). Such initiatives will be highly beneficial to the countries and organizations which are willing to use the latest technology for assessment of natural resources including crop status assessment. This is the first time that 'food security' has been featured in a global climate change accord called the Paris Climate Change Agreement 2015. The Agreement has recognized the fundamental need for prioritizing and safeguarding food security to end hunger (CCAFS, 2015). The global perspective toward food security has changed a lot since 1951. While in 1951, 'enough food to eat' was considered under FAO's goals; in 2011 'access to sufficient, safe and nutritious food with dietary preference' was taken into account (FAO, 1951; FAO, 2011). As per the FAO's report 'The state of food and agriculture review and outlook 1951', all countries were advised to take action in order to speed up the progress toward FAO's goal of ensuring that all humans had enough to eat, and of improving the living-standards of the mass of the world's population (FAO, 1951). The prospects of agricultural production were not encouraging and the danger of large scale hunger was looming. Since then a lot has changed in the agriculture sector. Population has reached record high levels and still continues to increase. Record food production has been achieved. However, the danger is not over. Shetty (2015) emphasized the need for a paradigm shift in policy formulation; from focusing on food security at the aggregate level to focusing on nutrition security at an individual level. It implies that the definition of 'food and nutrition security' assimilates both the conceptual frameworks of food security as well as nutrition security. There has been substantial improvement in the current situation of world hunger as compared to 1990's. A comparison of two FAO hunger maps of 1990-92 vs 2014-16 shows the overall reduction in world hunger especially in countries falling under 'High' and 'Vey high" categories (Figure 1.3). Many countries have improved their status by moving from 'Very high' category to 'High' category. Some countries have moved forward from 'High' hunger to 'Moderately high' while some other from 'Moderately high' to 'Moderately low' and 'Very low' hunger levels.

The World Summit on Food Security (2009) stated that 'availability, access, utilization and stability' are the four pillars of the food security. Availability refers to the supply of food through production, distribution and exchange. Access to food means the affordability and allocation of food combined with the preferences of individuals and household's requirements. While Utilization of food is the breakdown and subsequent usage of food by an individual's metabolism, Stability is the ability to obtain food over time. Food security has been considered such an important global issue that some thinkers see agricultural trade as a threat (Clapp, 2015).

1.2 Importance of Crop Area Estimation

All the above mentioned observations show that there is a multi-directional pressure on the land resources to meet the human population needs. This calls for a sustainable utilization of the available land resources in a way that doesn't have a detrimental effect on the ecological balance. Thus, efficient management of the available resources will play a major role.

Accurate and timely information on crop acreage is an important element of crop forecasting and efficient management of the crop products.

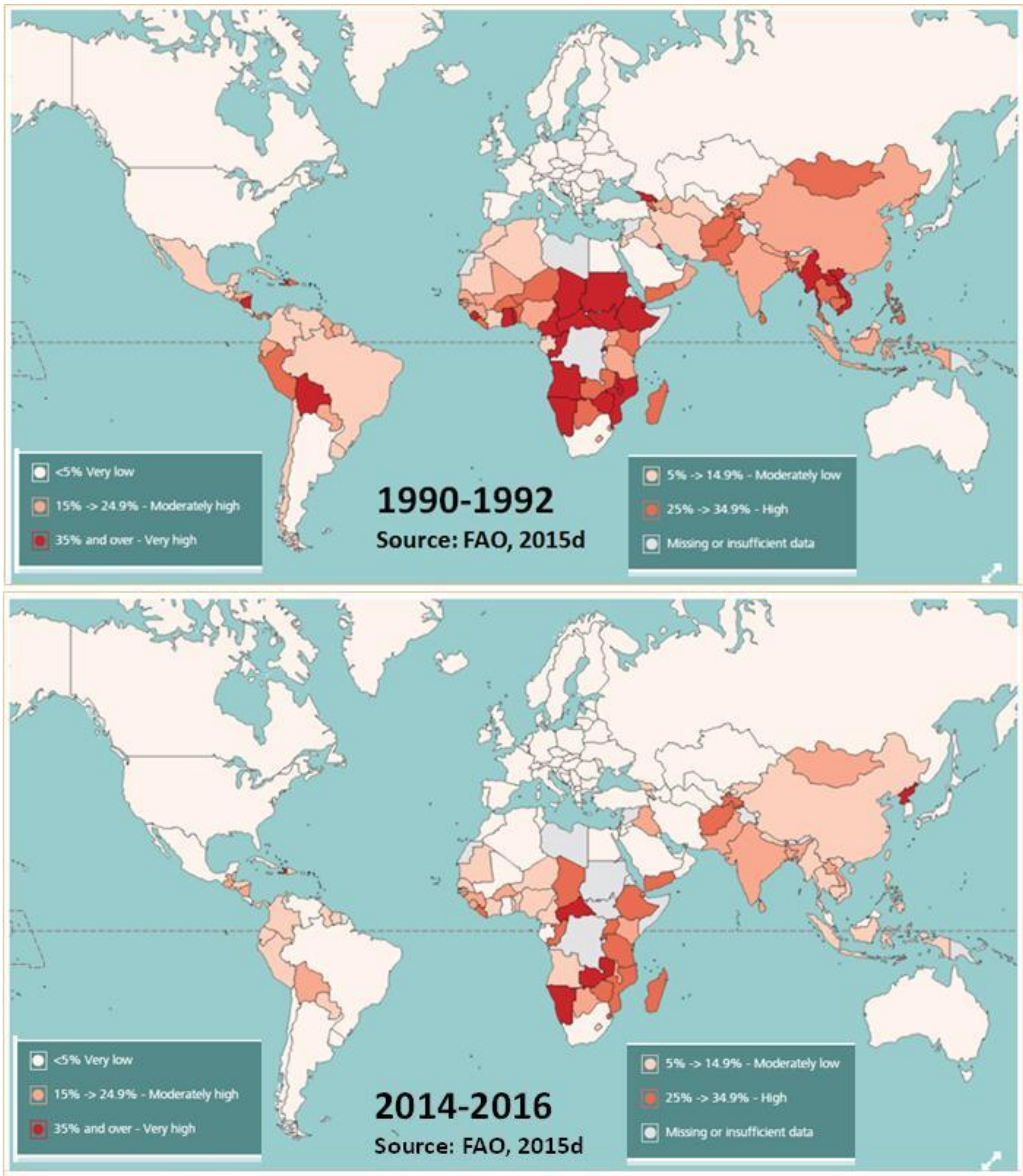


Figure 1.3. The World Hunger Maps 1990-1992 and 2014-16 Showing Spatial Distribution.

Agricultural planners, managers and decision makers need this information for forming agriculture policies related to import and export of the agricultural produce, and proper distribution of this output in order to meet the national requirement. Early information of crop sown area helps in the planning of distribution of irrigation water to meet crop water requirement. The supply and timely distribution of fertilizers also needs the information on spatial distribution of various crops.

India basically being an agriculture dominant country gets benefitted by agriculture sector in many ways. Other than fulfilling the national need for food supply, it also provides livelihood to a large population of the country. The contribution of agriculture sector to the national GDP has reduced from 43% in 1970s to 14% in 2013, yet almost 50% of India's workforce is still engaged in agriculture and its allied activities (PIB, 2012). It provides raw material to a large number of agro-industries associated with jute, cotton, sugar, tobacco, etc. India earns billions of dollars as foreign exchange every year by exporting its agricultural products such as jute, tea, tobacco, coffee, spices, and sugar etc. Hence, agriculture plays an immensely important role in the overall socio-economic fabric of the Indian society. Correct and timely information on crop products and crop sown area is needed by planners and policy makers for pricing, marketing, distribution, export/import etc.

1.3 Crop Acreage Estimation in India

Countries which produce substantial amounts of agricultural output have their own well-defined systems for Crop Acreage Estimation and Crop Production Forecasting. India has a traditional system for crop inventory and for getting estimates of various crops grown in different parts of the country. The estimates are integrated at different levels; from villages-to-districts-to-states levels and then to national level. These estimates are made available to decision makers. The country has a rich history of Crop Assessment System. It is said that Indian agriculture began around 9000 BCE with the cultivation of plants and domestication of crops. Trading in Indian crop-products with the world and the subsequent introduction of foreign crops to India through the traditional network, lead to the development of Crop Assessment System in India. The ancient Grand Anicut Dam built across the Kaveri River in India, for purposes of irrigation, is an evidence of a well-planned system of agriculture in ancient India. During the Mughal regime, Todarmal (a minister in Emperor Akbar's court) formulated and implemented various methods for land and agricultural management on a large scale. The Indian agricultural production got a major boost in the form of Green

Revolution in India. It was initiated in the 1960's through the introduction of High Yield crop varieties and application of modern agronomic technology.

From being a country largely dependent on imported food grains to a country exporting a number of food commodities to various other foreign countries, India has come a long way. Its population has increased almost 3.4 times since 1951 while its food grain production has increased by almost 5 times. The production of food grains has gone from almost 52 million tonnes in 1951-52 to almost 265 million tonnes in 2013-14 (ASG, 2014). Increasing trend of wheat production in India is shown in Figure 1.4.

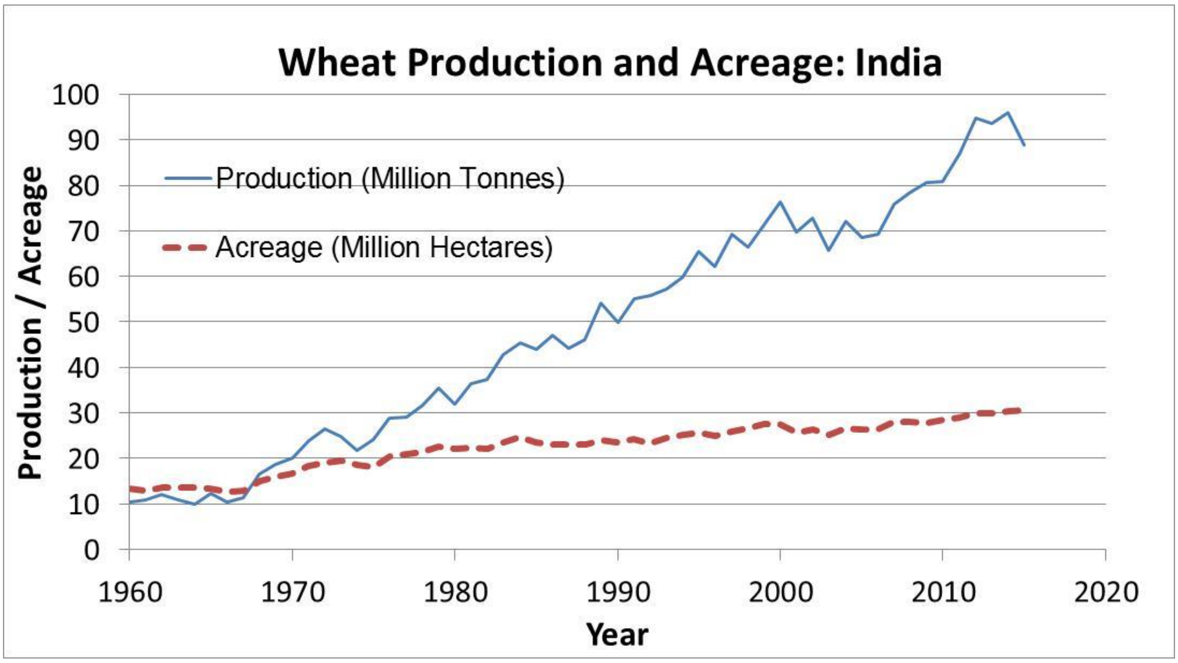


Figure 1.4. Wheat Production in India from 1960 to 2014 (Source: IndexMundi, 2015).

One more factor that is valuable for India's resource planners is that the population growth rate, which was higher compared to the world growth rate during 1970s to 2000s, has come down. The population growth rate comparison of India and the world is shown in Figure 1.5.

At present the Government of India assesses the agricultural status at different scales through different departments under the Ministry of Agriculture and Farmers Welfare. The agriculture statistics in India is collected through a decentralized system. The Directorate of Economics and Statistics (DES) in the Union Ministry of Agriculture and Farmers Welfare is responsible for coordinating and disseminating most of the national level agriculture statistics. This data is collected and compiled by the states according to the prescribed procedures. The government has a system of procuring four advance estimates and one final estimate of crop acreage and production, every year. The first advance estimate is available by the month of September. At this stage the South-West monsoon is almost over and the Kharif crops are nearing maturity stage. The final estimates are prepared by integrating the rough estimates provided by the state governments. The state government's estimates are based on mostly the visual observations carried out by their field officers working in the state agriculture departments.

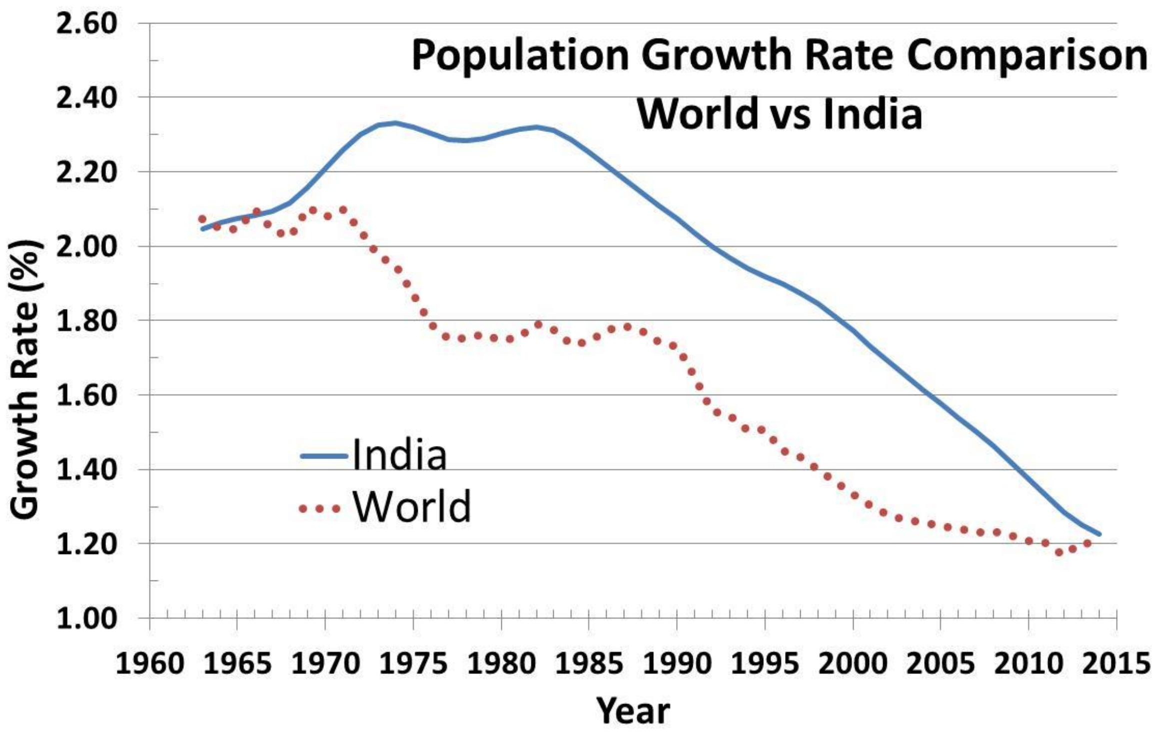


Figure 1.5. Comparison of Population Growth Rates (Source: World Bank, 2016b).

Every year in the month of January the second advance estimates having two components (the first assessment of the Rabi crops and the second assessment of the Kharif crops) are made. The third advance estimate is prepared towards the end of March or the beginning of April. The earlier estimates provided by the state governments are firmed up and validated through the inputs from other sources. The fourth advance estimate is made by June/July every year. By this time estimates of previous Kharif crops are almost final and Rabi crops also get harvested. This advance estimate includes the duly validated estimations of the previous Kharif crops, almost concluding assessment of Rabi crops and the likely assessment of summer crops. The final crop estimates are made available by December / January of the following agriculture year. The area statistics are collected through complete enumeration in major states and 4 union territories ('Land Record States' or 'Temporary Settled States') comprising around 86% of the reporting area. In three 'Permanently Settled States' namely Orissa, Kerala, and West Bengal, a scheme (EARAS i.e. Establishment of Agency for Reporting of Agricultural Statistics) based on total enumeration or area sampling method has been introduced to assess the crop area. It forms almost 9% of the reporting area. In other regions of the country, mostly the hilly, North-East and island regions, where no reporting agency is functioning, the village head is made responsible for reporting data for the crop area (ASG, 2014). This forms around 5% of the reporting area. Crop yield estimations are based on the Crop Cutting Experiments (CCE) conducted under a scientifically designed general crop estimation surveys. The procedure employed in conducting CCE has been presented with all the details by Man Singh (2012) and the design of CCE with support from RS data has been presented by Murthy et al., 1997.

One complete cycle of 4 advance estimates and one final estimate at the national level takes around 18 months to be completed. Two major factors are attributed to cause this delayed and time consuming procedure of crop statistics preparation. The first reason is that there are large variations in the crop calendar of crops across the country. The second reason is that, agriculture is a state government subject and hence the central government is dependent on the accurate inputs from the state governments' data collection systems. The state governments have setup high level committees which integrate input from different sources to get accurate estimates. It leads to delayed input to the central governments. Large scale efforts have been made and new schemes have been started by the central government to accelerate the process of crop assessment and statistics generation. Timely Reporting Scheme (TRS), Improvements of Crop Statistics (ICS), Establishment of an Agency for Reporting Agriculture Statistics (EARAS), and Forecasting Agricultural output using Space, Agro-meteorology, and Land based observations (FASAL) are some important steps that the government has taken to improve the system of crop assessment in India. Extensive efforts are made to incorporate the information obtainable from the latest available technologies and innovations. Crop inventory and crop assessment has shown a lot of improvement due to support from new technologies like satellite and aerial Remote Sensing (RS), Geographic Information System (GIS), Global Positioning System (GPS), Internet enabled mobile devices etc.

1.4 Crop Area Estimation and Remote Sensing

The basic principles of RS technique are presented in this section and a brief description on use of RS data for crop acreage estimation is given.

1.4.1 What is Remote Sensing?

Broadly defined, Remote Sensing is a technique of acquiring information about an object or phenomenon from a distance without making direct physical contact with the object. According to this definition, natural human activities like hearing through our ears, smelling through the nose, seeing through the eyes, are natural examples of remote sensing. While in the first two activities i.e. hearing and smelling the signals (sound and air mass, respectively) travel from the sources to the sensors (ears and nose, respectively) through the atmosphere; in the third activity, the light reaches the eyes with or without the presence of atmosphere. In both the cases the sensors don't make any physical contact with the objects which are observed or examined.

The term "remote sensing", first used in the United States in the 1950s by Ms Evelyn Pruitt of the U.S. Office of Naval Research, is now commonly used to describe the science—and art—of identifying, observing, and measuring an object without coming into direct contact with it. This process involves the detection and measurement of radiation of different wavelengths reflected or emitted from distant objects or materials, by which they may be identified and categorized by class/type, substance, and spatial distribution (Graham, 1999). In India, some of the earliest scientific literature on RS was written by Pisharoty (1983, 1991, 1993).

In contemporary practice, RS refers to detection, identification, and classification of the objects or the processes on the Earth (land surface, oceans, and atmosphere) by observing and recording their signals collected through aerial or satellite based sensors. There are a number of ways in which Remote Sensing has been defined in literature. Sanchez and Canton (1998) defined RS as the art and science of obtaining information about an object by a device that is not in direct contact with it. In a technological context, it usually refers to data gathered by sensors and instruments that measure emitted or reflected electromagnetic radiation which is formatted digitally so that it can be viewed pictorially or analysed by computers. It has been defined in multiple ways with core objective being remotely observing the object properties (Okamoto, 2001; Elachi and Zyl, 2006; Prost, 2013; Joseph and Kiema, 2013; Khorram et al., 2016).

The RS technology and the era of earth observation started with an oblique photograph of a village near Paris taken by Gaspard-Félix Tournachon (pseudonym Nadar) in 1858 from a balloon. Many people in different parts of the world followed him. Aerial photography from balloons played an important role during the Civil War in the United States, to disclose the defence positions in Virginia (Colwell, 1983). Since then a lot has happened in the field of photography and remote sensing. It developed technologically from balloon based platform to aerial and to satellite (polar as well as geostationary) based systems. It expanded from black and white photographs to coloured and false colour photographs, visible portion of electromagnetic radiation to IR (Infra-Red), TIR (Thermal Infra-Red), and microwave segments. Based on the type of sensor used to record the signal, RS can be divided in two classes: active and passive remote sensing. Active RS may be defined as the use of a transmitter and at least one receiver to record the reflected or scattered electromagnetic radiation. The RS systems which measure naturally available energy usually emitted or reflected /scattered from the objects, are called passive sensors. A schematic diagram showing a solar radiation based passive RS system is shown in Figure 1.6.

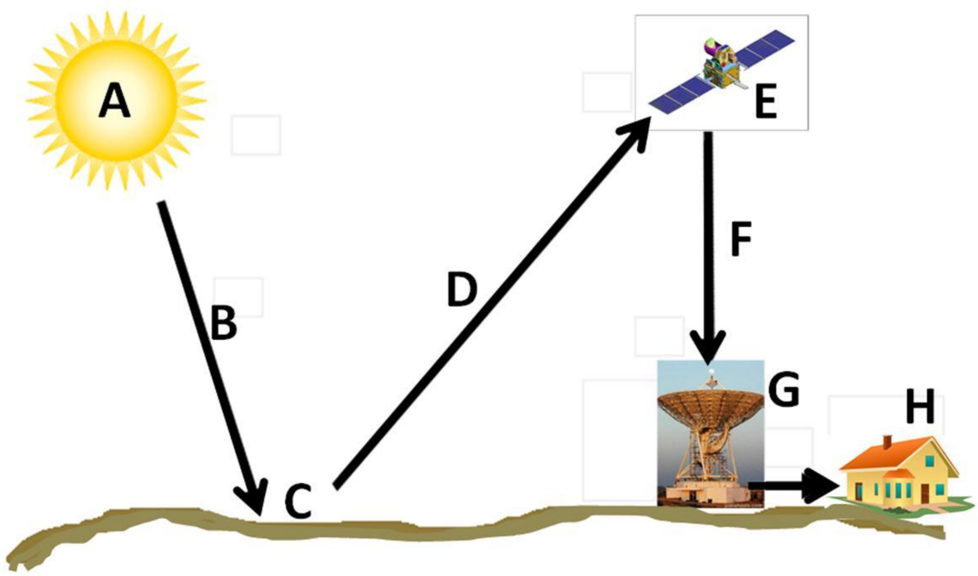


Figure 1.6. Major Elements of a Solar Radiation Based Passive RS System.

The Sun's radiation travel from 'A' through the atmosphere 'B' and interacts with the target 'C'. The radiation scattered/reflected from the target 'C' now travel through the atmosphere 'D' and is received by the satellite based sensor 'E'. The signal recorded at 'E' is then transmitted at different frequency through atmosphere 'F' to be acquired at data reception antenna 'G'. The data from receiving station is obtained by the analysts / subject experts and analysed in labs 'H' to derive the required information. A large number of satellites have been launched in space by various countries for earth observation. A list of the earth observation satellites launched by India since beginning (upto June 2016) is given in Table 1.1. The names of the major RS payloads carried by these satellites are also provided.

The satellite based remotely sensed data, collected through passive sensing and active sensing has been extensively used for crop inventory, area assessment, condition monitoring, yield prediction etc. In passive optical RS, the satellite based sensors measure the spectral radiance of the objects. The data collected over agriculture area shows different spectral signatures from crop area and non-crop area. When the spectral signatures of crops are distinctly different from that of non-crop land covers, it is easy to discriminate crops, classify them and estimate their coverage area. Many a times, the signatures are not unique and hence discrimination and classification of crops against other land covers becomes difficult and sometimes impossible.

Discrimination of crops using RS data depends on the type of data as well as the composition and the status of the crops with respect to its surroundings. In case of passive microwave RS of crops; the separation of the crops from other land covers depends on the difference of the emitted radiation from the crops and that from the surrounding along with the capability of the sensors to capture those differences. Microwave signal is transmitted and the backscattered signal is then recorded from the object under observation, in case of active microwave remote sensing. Dissimilar objects backscatter differently. Crop detection, identification, and discrimination depend on the characteristics of the sensing mechanism (viewing geometry, frequency, and polarisation) as well as the characteristics of the crops and its surrounding. Synergistic use of optical and microwave usually provides more information about the object than any single mode i.e. optical or microwave.

Table 1.1. The EO Satellites Launched by India (Source: ISRO, 2016).

Satellite	Launch Date	Launch Vehicle	Major Payloads
CARTOSAT - 2C	Jun 22, 2016	PSLV-C34	PAN
SARAL	Feb 25, 2013	PSLV-C20	AltiKa, ARGOS, SCBT
RISAT-1	Apr 26, 2012	PSLV-C19	SAR (C-band)
Megha-Tropiques	Oct 12, 2011	PSLV-C18	MADRAS, SAPHIR, ScaRaB, ROSA
RESOURCESAT-2	Apr 20, 2011	PSLV-C16	LISS-3, LISS-4, AWiFS, AIS
CARTOSAT - 2B	Jul 12, 2010	PSLV-C15	PAN
Oceansat-2	Sep 23, 2009	PSLV-C14	OCM, SCAT, ROSA
RISAT-2	Apr 20, 2009	PSLV-C12	SAR (X-band)
IMS-1	Apr 28, 2008	PSLV-C9	Mx, HySI
CARTOSAT – 2A	Apr 28, 2008	PSLV-C9	PAN
CARTOSAT-2	Jan 10, 2007	PSLV-C7	PAN
CARTOSAT – 1	May 05, 2005	PSLV-C6	PAN (Fore), PAN (Aft)
RESOURCESAT-1	Oct 17, 2003	PSLV-C5	LISS-3, LISS-4, AWiFS
TES	Oct 22, 2001	PSLV-C3	PAN
Oceansat(IRS-P4)	May 26, 1999	PSLV-C2	OCM, MSMR
IRS-1D	Sep 29, 1997	PSLV-C1	PAN, LISS-3, WiFS
IRS-P3	Mar 21, 1996	PSLV-D3	WiFS, MOS, IXAE, CBT
IRS-1C	Dec 28, 1995	Molniya	PAN, LISS-3, WiFS
IRS-P2	Oct 15, 1994	PSLV-D2	LISS-2A, LISS-2B
IRS-1E	Sep 20, 1993	PSLV-D1	LISS-1, MEOSS
IRS-1B	Aug 29, 1991	Vostok	LISS-1, LISS-2A, LISS-2B
SROSS-2	Jul 13, 1988	ASLV	GRB, MEOSS
IRS-1A	Mar 17, 1988	Vostok	LISS-1, LISS-2A, LISS-2B
RS-D2	Apr 17, 1983	SLV-3	Smart Sensor, L-band beacon
Bhaskara-II	Nov 20, 1981	C-1 Intercosmos	TV Cameras, SAMIR
RS-D1	May 31, 1981	SLV-3	Landmark Tracker
Bhaskara-I	Jun 07, 1979	C-1 Intercosmos	TV Cameras, SAMIR

1.4.2 Remote Sensing for Crop Area Estimation

RS signal from crops/vegetation is very different than that from most of the other land-cover classes by virtue of notable absorption in the red and blue segments of the visible spectrum along with higher reflectance in green segment and, importantly, it’s very strong reflectance in the near-IR due to total internal reflection.Use of remotely sensed data for large scale crop studies started in 1970’s in the United States of America. Two of the earliest successful studies were the Corn Blight Watch Experiment (CBWE) in 1971 and Large Area Crop Inventory Experiment (LACIE). Monitoring Agriculture with Remote Sensing (MARS) is a long term European endeavour to monitor the in-season weather and crop conditions and to estimate final crop yield by the harvest season. In MARS, crop growth is operationally monitored in near real time using RS information (Baruth et al., 2008). Crop Acreage and Production Estimation (CAPE) was the first large scale project in India that used remotely sensed data for crop studies.

A number of research studies and projects have demonstrated the usefulness of RS data in making crop inventory over different parts of the world (NASA, 1974; Mc-Donald and Hall, 1980; Tucker et al., 1980; Rao and Rao, 1987; Navalgund et al., 1991; Tennakoon et al., 1992; Sharman, 1993; De Mulder et al., 1993; Patnaik and Dadhwal, 1995; Kurosu et al., 1995; FAO, 1996; Oza et al., 1996; Moulin et al., 1998; FAO, 1998; Sun, 2000; Dadhwal et al., 2002; Rajak et al., 2002a; Thenkabail et al., 2002; Oza et al., 2002; Singh et al., 2002a; Singh et al., 2002b; Pinter et al., 2003; Dadhwal et al., 2003; Ray et al., 2005; Rajak et al., 2005; Potgieter et al., 2005; Parihar and Oza, 2006; Xiangming et al., 2006; Wardlow et al., 2007; JRC, 2008; Oza et al., 2008; Biradar et al., 2009; Rajak et al., 2011; Bailey and Boryan, 2010; Bhagia et al., 2011; Rembold et al., 2013; Vyas et al., 2013; Craig and Atkinson, 2013; Ray et al., 2014; Sud et al., 2015; Srivastava, 2015; Fritz et al., 2015; Parihar, 2016; Karam et al., 2016).

In India RS has been in use for crop area estimation since a couple of decades at different scales. Initially a number of studies were carried out to explore the potential of remotely sensed data for crop inventory, acreage estimation, and yield prediction. Later on Ministry of Agriculture and Department of Space in collaboration carried out large scale projects to demonstrate the application of optical and microwave RS data for crop studies. FASAL is the operational project which supports India in pre-harvest estimation of crop acreage and forecast of production of multiple crops on different scales.

1.6 Motivation for the Research

It is a fact well-accepted in scientific community that Remote Sensing (RS) is an important tool that provide near real time data which can be used for crop area estimation. RS data with different specifications (spatial, temporal, spectral resolutions etc.) are typically used for crop area estimation at different scales. The literature survey of RS based crop studies show that a lot of progress has taken place during last 3 to 4 decades of extensive development. A number of satellites have been launched by various countries in low earth orbits as well as geostationary orbits. Different types of sensors are developed in optical, infrared, thermal, and microwave segments of the electromagnetic spectrum. The sensors, operating in active or in passive mode, collect data related to earth's surface objects and atmosphere. The satellites stream terabytes of various kinds of data daily to data reception centres. This data has been used extensively by researchers, scientists, planners, and decision makes for a number of natural resources management applications. Data are collected with varied spatial, spectral, radiometric, and temporal resolutions. A large variety of data formats exist corresponding to different sensors and their characteristics. Researchers have developed many algorithms and techniques to analyse the variety of RS data and to extract the information they need.

As far as India is concerned, RS techniques are being used extensively for various natural resources inventory including crop inventory and monitoring. The RS data has been used for small area crop studies as well as for large area studies. While many studies used single date RS data, a number of studies have used multi-date RS data too. While working for national scale of projects and interacting with agriculture planners, I learned that there is a need of early estimation of crop area at small area level as well as at large area level. Extensive high spatial resolution (low temporal frequency) data as well as frequent low spatial resolution data are available over India. Currently there is no operational RS based system in India for an early estimation of Rabi crop area which is an important information needed by agriculture management agencies at multiple levels. Hence, lack of an early crop acreage estimation system needed by agricultural planners and availability of Multi-source / Multi-sensor Remote Sensing (MRS) data provided the motivational force to demonstrate the potential of MRS data for early estimation of crop sown area.

1.7 Outline of the Thesis

The **first chapter** of the thesis presents a general introduction of the research, beginning with the global concern of food security for the ever increasing population. It highlights the importance of agriculture sector in India and crop management. The agriculture sector satisfies the national need of food supply. Almost 50% of the India's workforce is engaged in agriculture and allied activities. It provides raw material to a large number of agro-industries associated with jute, cotton, sugar, tobacco, etc. Agriculture plays an immensely important role in the overall socio-economic fabric of Indian society. It emphasises the need for the correct and timely information on crop production and crop sown area which is needed by planners and policy makers for pricing, marketing, distribution, export/import etc.

Chapter 2 presents a review of the literature related to RS application for crop studies. The Earliest successful studies like Corn Blight Watch Experiment (CBWE), Large Area Crop Inventory Experiment (LACIE), to other large scale activities like Crop Acreage and Production Estimation (CAPE), Monitoring Agriculture with Remote Sensing (MARS), China CropWatch System (CCWS) etc. are discussed. A number of RS studies in India and abroad, related to crop area assessment and crop monitoring have been discussed. Crop studies carried out at all scales i.e. village scale to regional scale have been included. A brief review of RS data studies on classification schemes has also been presented. The chapter presents the identified research gap area, accordingly framed research questions, and objectives of the study.

Chapter 3 presents the research methodology including the basic algorithms and data mining techniques adopted in this research investigation. Radiometric normalisation of multi-date MODIS data by Harmonic ANalysis of Time Series (HANTS), major RS data classifiers used in the investigation i.e. supervised maximum likelihood classifier, unsupervised K-means, unsupervised Iterative Self-Organising Data Analysis Technique (ISODATA) based clustering, and decision tree classifiers are discussed. The approach for assessing the classification accuracy of the classified images and the acreage estimates is also presented.

Chapter 4 describes the study area, data used, methodology, and the results of a sub-study carried out to develop a technique for early estimation of Rabi crop sown area at district level using MRS data. It discusses the major challenges faced during the integrated use of multi-source data. The procedure to be followed for resolving such issues has been discussed. Multi-date data from Resourcesat-2 AWiFS and 1-date data Resourcesat-2 LISS-III sensors were used for early estimation of crop acreage in Mehsana district of Gujarat state in India. This technique made use of the temporal information of crop growth embedded in the high frequency data (AWiFS) and spatial information embedded in low frequency data (LISS-III).

A technique developed for early estimation of crop sown area using multi-source data at state level (the geographic area of the study state is around 20 million hectares) has been presented in **Chapter 5**. A methodology of early estimation of crop sown area at large scale by making use of high temporal coarse spatial resolution data and low temporal moderate spatial resolution data has also been presented. This sub-study also made use of previous years' data for extracting a-priori information of crop sowing area. While ISODATA (Ball and Hall, 1965) was used for classifying multi-date MODIS and AWiFS data; hierarchical decision tree approach was used for integrating multi-source information. Incorporating two date AWiFS data and a-priori information with multi-date MODIS data significantly increased the accuracy of crop sown area estimates.

It has been demonstrated in **Chapter 6**, that multi-date multi-year moderate resolution data can be used for assessing multi-year crop changes at state level. The multi-date 8-day surface reflectance data of Terra MODIS over Gujarat state (India) for 10 years has been used. Based on the analysis of multi-year Normalized Difference Vegetation Index (NDVI) time series data from 2002-03 to 2011-12, it is concluded that (i) temporal smoothing of the time series MODIS data is required; (ii) performance of HANTS algorithm over this data was found to be satisfactory; (iii) there is considerable increase in area under Rabi season crops in Gujarat from 2002-03 to 2011-12; and (iv) MODIS data can be used for monitoring gross annual changes of major Rabi crops at regional scale.

The results obtained through three sub-studies are discussed in **Chapter 7**. The results are also discussed in respect to the research questions and the thesis summary is presented. The last chapter, **Chapter 8** concludes the thesis with Summary, Limitations, Conclusions and Future Scope of the research.

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