Crop Yield Estimation: Integrating RS, GIS and Management Factors

A CASE STUDY OF BIRKOOR AND KORTGIRI MANDALS – NIZAMABAD DISTRICT, INDIA

HAIG L. A. SAWASAWA

MARCH 2003

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By

Haig L. A. Sawasawa

Thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfillment of the requirements for the degree of Master of Science in, Geo-information Science and Earth Observation; Sustainable Agriculture

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March 2003

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Key words: NDVI, Remote sensing, Field level, yield estimation.

Abstract

Early prediction of crop yield is important for planning and taking various policy decisions. Many countries use the conventional technique of data collection for crop monitoring and yield estimation based on ground-based visits and reports. These methods are subjective, very costly and time consuming. Empirical models have been developed using weather data, which is also associated with a number of problems due to the spatial distribution of weather stations. These models are complex in terms of data demand and manipulation resulting in information being available very late, usually after harvesting.

Efforts are being done to improve the accuracy and timeliness of yield prediction methods. With the launching of satellites, satellite data is being used for crop monitoring and yield prediction. Many studies have revealed that there is correlation between remotely sensed NDVI and yield. However, most of these studies have been done at regional or national level using low-resolution images, resulting in a lot of generalisations. Studies done at research stations using low flying platforms or hand held equipment to collect spectral data, have also indicated similar relationships.

This study applied space-borne satellite based NDVI to predict crop yield at field level. It was carried out in India, Andhra Pradesh state (Birkoor and Kortgiri Mandals, Nizamabad district). The purpose of the study was to investigate the relationship between space-borne Satellite based NDVI and rice yield in irrigated fields, and combining NDVI with management and land factors for yield prediction at field level.

Data was collected through interviewing farmers on the management practices and yield for the Rabi season, December 2001 – April 2002. Land data for the area was available in form of shape files and tables. Stepwise linear regression was used to relate yield to the management and land factors and the NDVI and to derive a yield estimation model.

The results showed that there is significant correlation between remotely sensed NDVI and field level rice yield ($r = 0.52$, $p = 0.00$). It was found that NDVI explained 25.0% (R^2_{adj}) of the yield variability at field level. Land and management factors accounted for 38.1% (R^2_{adj}) of the yield variability. A combination of all the factors including NDVI explained 45.8% (R^2_{adj}) of the yield variability. The study also showed that not all the factors affecting yield also affect NDVI.

Acknowledgement

The completion of this paper came with the assistance from many people whom mentioning each one may not be exhaustive. However, I wish to express my sincere appreciation and gratitude to all the people who contributed towards this work in one way or another. I would like to pay special thanks and appreciation to God, the Almighty, who have made it possible for my stay here and completed all the work.

My special gratitude also goes to the government of the Republic of Malawi, through the Department of Land Resources and Conservation for appointing me and approving my studies, and providing all the necessary support. I would like to specifically thank Mr J. Mulenga (Director of Land Resources and Conservation Department) for considering me as a possible candidate for this special study, Mr J. Mussa (Deputy Director – LRCD, Training) for putting up the fight that materialised into the award of my Scholaship.

I deeply appriciate the efforts of my primary supervisor, Dr Kees de Bie, whose guidance, vast experince, has assisted in the production of this paper. Despited the pressure of work, he spent his time to listen and assist and offering guidance. I thank also Dr H. Huizing for his support and suggestions towards this study.

I would like to acknowledge the National Remote Sensing Agency of India for the support and providing the data that complemented this study. I thank specifically Uday Nidumolu who made my preparation for field work and data collection in India easier and offered the assistance I required while in India and in the Netherlands.

I thank the Indian people, especially the farmers in Birkoor and Kortgiri Mandals for their co-operation and support during field data collection. I also thank Mr Kushal, Mr Jatin Kumar, Mr. Luka for the work they did in guiding and bridging the communication gap between the farmers and myself. I also thank the driver for all the work he did while in India.

My thanks will not be complete if I do not mention my MSc classmates in our cluster, Charles, Mohammad, Tiejun, Abaye, Gedion, Jenna, Alexander, Devika – you are great people. Andrew, Rodrigo, that was a good company. My fellow country men, Esther and Mavuto, your support can not be forgotten.

Amon and Mohammed, your comments, I appreciate.

To
My mother Nellie Sapakudwe,
My wife Clotilda
And the little ones,
Thokozani, Takondwa and Nafe

"18 months has not been so easy without you guys!"

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1 Introduction

1.1 Background

Rice is the world's most important staple food crop. According to the FAO (2001), four fifth of the worlds rice is produced and consumed by small-scale farmers in low income developing countries where more than half of the population relies on rice as the major daily source of food.

During the green revolution the increase in the world's rice production has resulted in more rice being available for consumption. Despite the increase in production, still many people in the world are suffering from hunger and malnutrition; most of them live in areas that depend on rice production for food, income and employment (FAO 2001).

Rice production, consumption and trade are concentrated in Asia and mainly dominated by countries situated in the belt from Pakistan in the west and Japan in the east (FAO 2000b). These countries account for more than 90% of the world's rice production. It is a staple food for more than 2.7 billion people in Asia, providing between 35 and 60% of the food energy.

Rice is mainly grown in four major production ecosystems which are broadly defined on the basis of water regimes; irrigated rice, rain fed lowland rice, upland rice and deep water rice. Irrigated rice accounts for 71% of the total rice output, rain-fed lowland rice 19%, upland rice 7% and deep water rice 4%

Worldwide, India stands first, after China, in rice area and second in rice production. It contributes 21.5% of the total global rice production (FAO 2000b). Within the country, rice occupies one quarter of the total cropped area, it contributes 40 to 43% of the total food grain and plays an important role in the national food and livelihood security system. A combination of increased area and higher cropping intensity transformed India from a net importer to a potential exporter of quality rice (FAO 2000b).

1.2 The need for crop yield forecasting

Forecasting crop yield well before harvest is crucial especially in regions characterised by climatic uncertainties. This enables planners and decision makers to predict how much to import in case of shortfall or optionally, to export in case of surplus. It also enables governments to put in place strategic contingency plans for redistribution of food during times of famine. Therefore, monitoring of crop development and of crop growth, and early yield prediction are generally important.

Crop yield estimation in many countries are based on conventional techniques of data collection for crop and yield estimation based on ground-based field visits and reports. Such reports are often subjective, costly, time consuming and are prone to large errors due to incomplete ground observations, leading to poor crop yield assessment and crop area estimations (Reynolds *et al.* 2000). In most countries the data become available too late for appropriate actions to be taken to avert food shortage.

In some countries weather data are also used (de Wit & Boogaard 2001, Liu & Kogan 2002) and models based on weather parameters have been developed. This approach is associated with a number of problems including the spatial distribution of the weather station, incomplete and/or unavailable timely weather data, and weather observations that do not adequately represent the diversity of weather over the large areas where crops are grown (Dadhwall & Ray 2000, de Wit & Boogaard 2001, Liu & Kogan 2002, Rugege 2002).

Objective, standardised and possibly cheaper/faster methods that can be used for crop growth monitoring and early crop yield estimation are imperative.

Many empirical models have been developed to try and estimate yield before harvesting. However, most of the methods demand data that are not easily available. The models complexity, their data demand, and methods of analysis, render these models unpractical, especially at field level.

With the development of satellites, remote sensing images provide access to spatial information at global scale; of features and phenomena on earth on an almost real-time basis. They have the potential not only in identifying crop classes but also of estimating crop yield (Mohd *et al.* 1994); they can identify and provide information on spatial variability and permit more efficiency in field scouting (Schuler 2002). Remote sensing could therefore be used for crop growth monitoring and yield estimation.

1.3 Yield estimation in India

India underwent a series of successful agricultural revolutions, starting with the "green" revolution in wheat and rice in the 1970s, the "white" revolution in milk and, in the 1980s, the "yellow" revolution in oil seeds. Despite these major transformations, the agricultural sector continues to be dominated by a large number of small landholders (70 % of rural people and 8 % of urban household depend on agriculture). The country is also marked by large fluctuations in agricultural output, though to a declining extent with the development of irrigation facilities, adoption of new technologies and changes in cropping patterns (FAO 2000a). Figure 1.1 shows the trend of rice production, yield and cropped area since 1951.

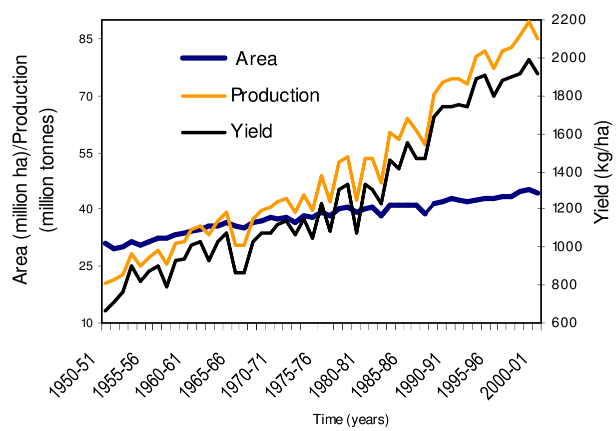


Figure 1.1 Rice production and yield trend for India since 1951.

The traditional approach of crop estimation in India involves complete enumeration (except in a few states where sample surveys are employed) for estimating crop acreage and sample surveys based on crop cutting experiments (CCE) for estimating crop yield. The crop acreage and corresponding yield estimate data are used to obtain production estimates.

These yield surveys are extensive; plot yield data being collected under complex scientifically designed sampling design that is based on a stratified multistage random sampling (Government of India 2002, Singh *et al.* 1992, Singh *et al.* 2002) figure 1.2.

Final production estimates based on this sampling method become available after the crops are actually harvested. Although the approach is fairly comprehensive and reliable, there is a need to reduce the cost and also to improve upon the accuracy and timeliness of crop production statistics.

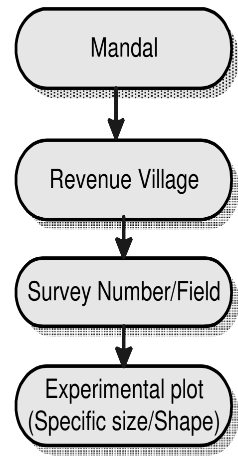


Figure 1.2 Sampling design for CCE

Yield estimates predicted before actual production are required for taking various policy decisions. Hence, early assessment of crop yield is necessary, particularly in countries that depend on agriculture as their main source of economy. It enhances timely provision of information for use in food security.

In India, there is also a growing need for micro-level planning and particularly the demand for crop insurance (Singh *et al*. 2002), which increases the need for field level yield statistics.

At present, there is no model that relates field level yield to NDVI and no simple method that produces quantitative pre-harvest data accurately and in time.

With the successful launching of satellites like IRS-1A and 1B in 1998 and 1991 respectively, and other previous satellites, a lot of efforts are made to use remote sensing for yield estimation.

To achieve timely and accurate information on the status of crops and crop yield, there is need to have an up-to-date crop monitoring system that provides accurate information on yield estimates way before the harvesting period. The earlier and more reliable information the greater the value (Hamar *et al.*1996, Reynolds *et al*. 2000). Remote sensing data has the potential and the capacity to achieve this.

1.4 Problem Statement

Remote sensing has been used extensively as a tool to assess and monitor vegetation parameters, crop vigour and yield estimation. Regional and national early warning systems have been established in Africa to provide advance warning of drought that may cause temporally or prolonged food shortage (Rasmussen 1997). It has been shown that remote sensing data provide systematically high quality spatial and temporal information about land surface features including environmental impacts on crop growth conditions (Liu & Kogan 2002). Most studies have established that there is correlation between NDVI and the green biomass and yield, therefore, NDVI can be used to estimate yield before harvesting (Gat *et ai.* 2000, Groten 1993, Liu & Kogan, 2002, Rasmussen 1997).

However, these studies were mostly done at regional/national level covering very large areas. Since they cover very large areas, low-resolution images were used resulting into generalisation of the crop condition and yield estimates. The coarse resolution also had a mixture of crops and other non-crop vegetation that contributed to the NDVI value, which later was correlated to the final crop yield.

Other studies were done at field level and reported high correlation between NDVI and yield. However, most of these studies were done under research conditions involving very small plots with spectral data being collected with ground-based platforms extended over the plots or low flying platforms. Such conditions enable a large degree of control over many extraneous factors and normally result in high quality data and excellent correlation between the measured and remote sensed data (Staggenborg & Taylor 2000). Quarmby *et al.* (1993) showed that NDVI can be used to estimate yield from a test field in Greece and Verma *et al* (1998), working on gram, found high correlation between NDVI and dry matter. The potential of regression models to estimate crop yield more accurately under variable management conditions was clearly established.

However, relatively few studies on the relationship between remote sensed data and field scale crop yield have been conducted (Staggenborg & Taylor 2000). At this scale agricultural production is a result of complex environmental stresses including farmers' management. These have a great effect on the final yield, which may not be detected with very low resolution satellite images or highly controlled experiments. This study, therefore, proposes to estimate crop yield at field level where the final yield is a translation of various extraneous environmental and management factors by applying remote sensed NDVI.

1.5 Research objectives

1.5.1 General objective of the study

Many studies on the relationship between remote sensed data and crop yield have been done either on research involving very small areas with very high degree of control of many parameters affecting crop growth and production or on very large areas, which tend to generalise information. Few studies have applied remote sensing data at farmers' field level to estimate yield. In this study, remote sensed data was used to estimate yield at field level where crop growth and yield is a translation of complex environmental factors including management.

The primary objective is to establish the relationship between remotely sensed NDVI measurements and field level yields by integrating other production factors (Land and Management) at field level.

1.5.2 Specific objectives

1. To establish the relationship between NDVI and field level crop yield in irrigated rice.
2. To assess and establish the relationship between NDVI, field level management practices and land factors for crop yield estimation.
3. To assess the possibility of using a single date multi-spectral image for yield prediction.

1.6 Research questions

To achieve the stated objectives the following questions will be answered.

1. What is the relationship between remote sensed NDVI and crop yield at field level?

2. Does NDVI reflect crop management practices at field level and the quality of land?
3. Can NDVI derived from a single date multi-spectral image be used to explain yield variability at field level?

1.7 Hypotheses

Vegetation density is the most obvious physical representation of subsequent yield from crops. The density and health can be monitored using remotely sensed images that measure chlorophyll activity and vegetation vigour. The spectral reflectance is a manifestation of all important factors affecting the agricultural crop and cumulative environmental impacts on crop growth (Liu & Kogan 2002, Singh *et al.* 2002), therefore remote sensed data could be used to monitor crop condition through NDVI.

Management practices in the production system and how land is utilised will have an effect on the overall productivity. In this respect, crop growth and crop yield is a response to the type of management and the quality of the land unit.

Based on the above, hypothesis adopted in this study are as follows:

1. There is significant relationship between NDVI, and yield at field level.

$$\text{Yield} = f(\text{NDVI})$$

2. There is significant relationship between NDVI, field level management and land.

$$\text{NDVI} = f(\text{Land, Management})$$

3. Single date multi-spectral images can be used to predict yield at field level.

Integrating hypothesis 1 and 2 leads to:

$$\text{Yield} = f(\text{NDVI, Land, Management})$$

Where only those land and management factors remain relevant that have no impact/relation with NDVI, the rest are now no longer relevant.

1.8 Assumption

The spectral reflectance of crops is strongly related to canopy parameters, which are related to the final yield. These parameters are influenced by factors such as genotype, soil characteristics, cultural practices and other biotic factors i.e. spectral data is an integration of all the factors affecting crop growth.

2 Concepts

2.1 The spectral response of vegetation

Green plants have a unique spectral reflectance influenced by their structure and composition. The proportion of radiation reflected in different parts of the spectrum depends on the state, structure and composition of the plant. In general, healthy plants and dense canopies, will reflect more radiation especially in the near infrared region of the spectrum.

In the visible part of the spectrum (0.4 µm – 0.7 µm), plants absorb light in the blue (0,45 µm) and red (0.6 µm) regions and reflect relatively more in the green portion of the spectrum due to the presence of chlorophyll. High photosynthetic activity will result in lower reflectance in the red region and high reflectance in infrared region of the spectrum. In cases where plants are subjected to moisture stress or other conditions that hinder growth, the chlorophyll production will decrease, This in turn leads to less absorption in the blue and red bands (Dadhwall & Ray 2000, de Wit & Boogaard 2001, Janssen & Huurneman 2001, Woldu 1997).

In the near-infrared portion of the spectrum (0.7 – 2.5 µm), green plants reflectance increases to 40 – 60%. Beyond 1,3 µm, there are dips in the reflectance curve due to absorption by water in the leaves, more free water result in less reflectance. Figure 2.1 shows an ideal reflectance curve from healthy vegetation.

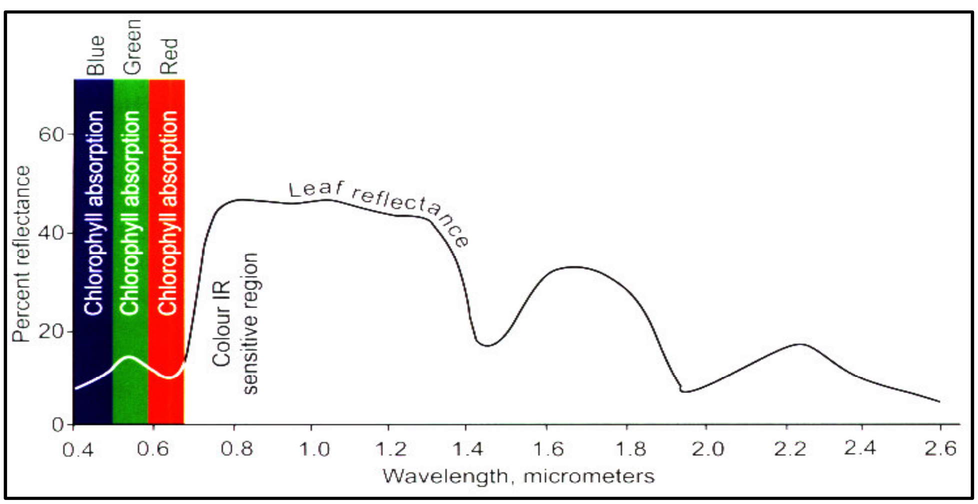


Figure 2.1 Idealised spectral reflectance of healthy vegetation

Source: Janssen and Huuenemen (2001)

As the leaves dry out or as the plant ripens or senescence or become diseased or cells die, there is reduction in chlorophyll pigment. This result in the general increase in reflectance in the visible spectrum and a reduction in reflectance in the middle infrared (MIR) portion of the spectrum due to cell deterioration. Thus, the spectral response of a crop canopy is influenced by the plant health, percentage of ground cover, growth stage, differences in cultural practices, stress condition and the canopy architecture (Verma *et al*. 1998).

This differential reflection of green plants in the visible and infrared parts of radiation makes it possible for the detection of green plants from satellite data because other features on earth surface do not have such unique step-like characteristics in the 0.65 – 0.75 µm spectral range. This signature is unique to green plants only and thus this principle is used in vegetation indices.

2.2 Vegetation Indices

Based on this concept, many vegetation indices (VIs) have been developed that have specific features concerning the range of vegetation cover. VIs have been used since the Landsat satellite became operational. The vegetation indices provide information on the state of vegetation on the land surface; vegetation is the result of a complex relation between land and land use, and provides thus a means of monitoring and estimating changes over time (Dadhwall & Ray 2000, de Wit & Boogaard, 2001, Gielen & de Wit 2001). The commonly used VIs include:

2.2.1 Ratio Vegetation Index (RVI)

This is the simplest form of ratio-based vegetation indices calculated through the use of infrared and the Red band of the electromagnetic spectrum. It is calculated as follows;

$$RVI = \frac{IR}{R}$$

Where:

RVI = Ratio Vegetation Index
IR = Infrared band of the electromagnetic spectrum
R = Red band of the electromagnetic spectrum.

This VI seem to be more affected by the noise present in the image due to atmospheric condition (Gielen & de Wit, 2001).

2.2.2 Normalised difference Vegetation Index (NDVI)

This vegetation index is a ratio based VI calculated by the difference of the infrared and red bands as rario to their sum. Thus:

$$NDVI = \frac{IR - R}{IR + R}$$

Where:

NDVI = Normalised Difference Vegetation Index

IR = Infrared band of the electromagnetic spectrum

R = Red band of the electromagnetic spectrum.

Through this normalisation, the values are scaled between –1 and +1.

RVI and NDVI are related to vegetation amount until saturation at full canopy cover and are therefore related to the biophysically active radiation, efficiencies and productivity (Rondeaux *et al.* 1996).

2.2.3 Other vegetation indices

Other vegetation indices that take into account the soil effect on vegetation reflectance, especially at low vegetation levels, have been developed. These indices assume a linear relationship between near infrared and the visible reflectance from bare soil. These VIs provide better results than NDVI at low vegetation cover because they eliminate the soil background effect. These VIs include Perpendicular Vegetation Index (PVI), Weighted Difference Vegetation Index (WDVI), Soil Adjusted Vegetation Index (SAVI), Transformed Soil Adjusted Vegetation Index (TSAVI) and the more recently introduced Modified SAVI (MSAVI) (de Wit & Boogaard 2001, Huete 1988, Qi *et al.* 1994, Rondeaux *et al*. 1996). For details see appendix 4.

Out of all VIs, the Normalised Difference Vegetation Index (NDVI) stands out and is regarded as an all-purpose index. This VI is the most widely used and well-understood vegetation index (de Wit & Boogaard 2001). It is simple to calculate, has the best dynamic range and has the best sensitivity to changes in vegetation cover (Gielen & de Wit 2001). It has been found to correlate better with yield than other vegetation indices and thus continues to be used as a vegetation/biomass indicator using remotely sensed data (Andrew *et al.* 2000, Mohd *et al*. 1994, Singh *et al*. 2002).

2.3 Rice growth and production – Phenological stages

The main growth stages of rice was described by University of Arkansas (1997). The information was applied to the rice variety IR64, a high yielding, semi dwarf variety; it also generally applies to all rice varieties.

The rice life cycle is mainly divided into three phases; 1) Vegetative: from germination to panicle initiation, characterised by active tillering, gradual increase in plant height and leaf emergency, 2) reproductive phase: from panicle initiation to flowering, and phase 3) ripening phase: from flowering to grain maturity. In tropical regions the reproductive phase is about 35 days and the ripening phase is about 30 days. The phases have each distinctive growth stages consisting each of about 10 day periods. Stages 0 - 3 encompasses the vegetative phase, stages 4 - 6 the reproductive phase and stages 7 - 9 correspond to the ripening phase.

2.3.1 Vegetative phase:

Stage 0 - Germination to emergency. The process involves the protrusion of the radicle and plumule from seed and subsequent emergence from the soil.

Stage 1 - seedling stage. Starting from just after emergency to just before the first tiller is produced.

Stage 2 - tillering. It starts when the first tiller appears and lasts until the maximum of tillers are produced. At this stage the plant increases in length. Leafing and primary and secondary tillering is very active.

Stage 3 - stem elongation. The stage commences at the end of tillering. Tillers continue to increase in height without appreciable senescence of leaves resulting in advanced ground cover and canopy formation by the growing plants. The growth duration of rice is related to stem elongation.

This stage is longer in long duration varieties than short duration varieties. Figure 2.2 illustrates the life cycle of two different rice varieties with different growing periods.

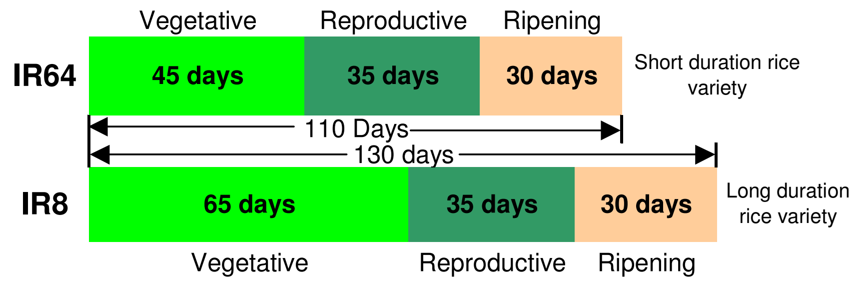


Figure 2.2 Rice growth stages.

2.3.2 Reproduction phase:

Stage 4 – panicle initiation to booting. The start of this stage is marked by the visibility of the panicle primordium. At booting, senescence of leaves and none bearing tillers increases and becomes noticeable.

Stage 5 – Heading. Marked by the emergence of the panicle tip from the flag leaf.

Satge 6 – Flowering. Begins with the appearance of anthers.

2.3.3 Ripening phase:

Stage 7- milk grain stage. The grain starts to be filled with white, milky liquid. The panicles still looks green and starts to bow down.

Stage 8 - dough stage. The grain turns into soft dough and then hard dough. The grain in the panicle starts to turn yellow. Senescence of leaves and tillers increases.

Stage 9 – grain maturing stage. The final stages in the life cycle of rice. The individual grain is mature and has turned yellow. Upper leaves now start to dry and a considerable amount of dead leaves accumulate at the base of the plant.

3 Materials and Methods

3.1 Study area

3.1.1 Location

The study was conducted in Nizamabad district in Andhra Pradesh state in India. The district covers an area of 7947 km^2. It is generally flat, having mostly slopes of less than 3%. The district is divided into 36 Mandals (district sub-units) and has a total of 923 villages. It is bounded by Nandhed district of Maharashtra State on the west and Adilabad district in the North, Medak district on the South and Karimnagar district on the East.

This study was conducted in two Mandals of the district, covering 70 villages. The mandals include Birkoor with 31 villages and Kortgiri with 39 villages. These mandals are located between 77^o 35' – 78^o 00' E and 18^{o}15' –18^o 40' N (see figure 3.1).

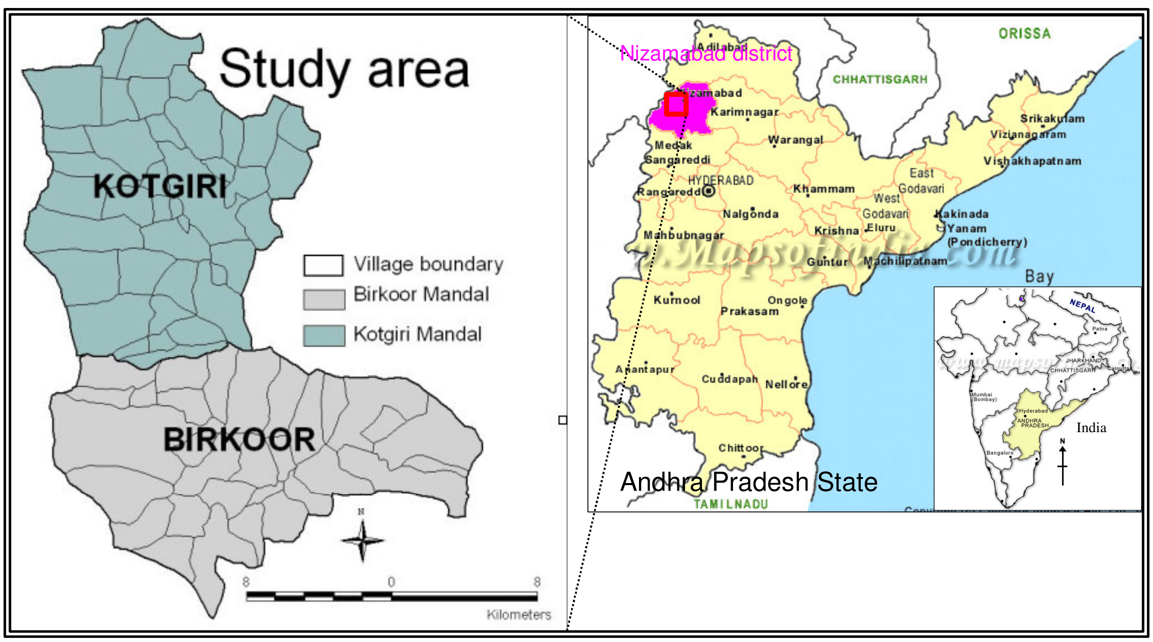


Figure 3.1 Study area (Kortgiri and Birkoor mandals - Nizamabad, India).

3.1.2 Population

The district has a total population of 2,342,803 of which 18.03% live in urban areas . It has a density of 242 persons per square kilometre, (Nizamabad District 2001). Kortgiri mandal covers an area of 187.4 km^2 with a population of 51,566 and Birkoor has an area of 188.9 km^2 with a population of 44483. In these two mandals, the population is 100% rural. 9.61% in Kortgiri and 18.18% in Birkoor are farmers, 30.7% and 26.3% are agricultural labours in Kortigiri and Birkoor respectively, and the rest are employed in other small scale trades (Nizamabad District 2001).

3.1.3 Climate

Climate is predominately semi-arid to arid. In general, there are four seasons in the district. Hot weather (from March to may), Southwest monsoon (from June to September), Northeast monsoon (from October to December) and winter (from December to February).

The sate of Andhra Pradesh is divided into seven zones based on the agro-climatic conditions. The classification mainly concentrates on the range of rainfall received, type of the soils and topography. Nizamabad falls in the Northern Telagana Zone including Adilabad, Kwinnager districts and parts of Warangal, Khammah, Medak and Nalgoda districts.

Rainfall: Telagana zone is in the semi-arid track. It receives an average annual rainfall of 900 - 1150mm. Most of which come from southwest monsoon and the northeast monsoon. The rains normally begin in the second week of June and lasts till September (Southwest monsoon), which marks the main growing season (locally known as Kharif). The month of July is when the area receives most of its rain. The second rainfall occurs in October-November. Winter starts in December and lasts till March (locally known as Rabi season) and crop production is through irrigation. No or very little rainfall is expected during this period. Figure 3.2 shows the monthly rainfall distribution for six years (figure 3.2a) and rainfall variability between years, figure 3.2(b).

Temperature: Summers are hot but after the rain begins in the middle of June, there is a decline in the temperature. Lowest temperatures are recorded in December. In April and May, on individual days temperature may go up to more than 40 ^{o}C. However, annual mean maximum temperature varies between 30-37^{o}C and mean minimum temperature vary between 21 – 25^{o}C. Figure 3.3 shows the mean maximum and mean minimum temperature fluctuations throughout the year from 1998 to 2001. Sometimes the temperatures may go down to 13 -15^{o}C in winter and as high as 45^{o}C in summer.

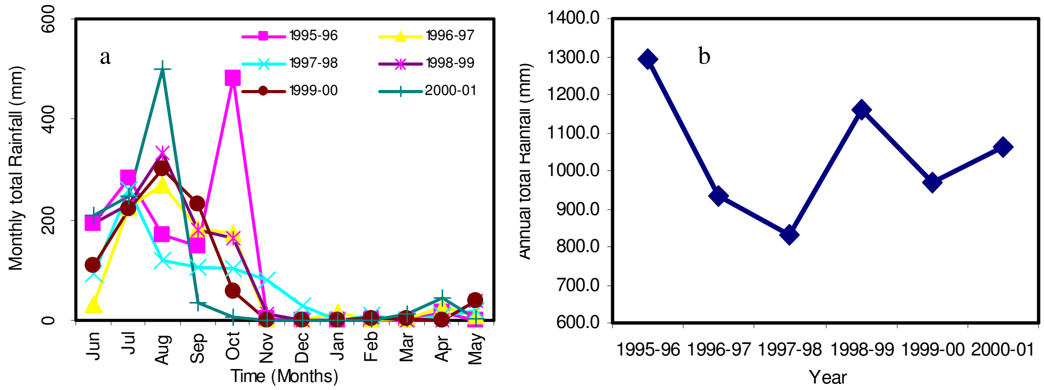


Figure 3.2 Monthly rainfall distribution (a) and Annual rainfall variability (b).

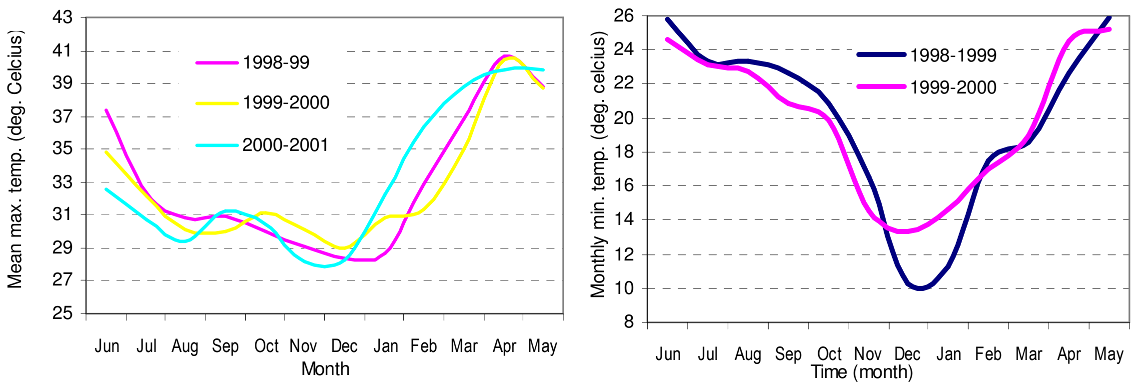


Figure 3.3 Mean maximum and minimum temperatures for Nizamabad district.

Soil

The area is covered with different soils. These soils, according to Venkateswarlu (2001) include the red soils (Locally known as "Chalkas") (covering 358,000 ha of the district) and black soils (270,000 ha). The red soils are mostly the Alfisols, Inceptisols and Entisols formed from granite and gneisses. The soils are regrouped into six sub-groups due to varying in mineralogical composition, relief and topography (Rao *et al.* 1995).

However, based on the data available, and the characteristics of the soils from the area, the soils were regrouped into five most practical sub-groups (Rossiter 2002). Sub-group A, soils having high proportion of clay, shrinks and very sticky. Sub-group B, soils that are shallow (skeletal soils) and have low water holding capacity. Sub-group C, is medium textured, deep, fertile soils. Sub-group D, are soils that are course textured, fertile with low water holding capacity. Sub-group E soils which are regularly flooded, layered, fresh soil material from periodic flooding.

Figure 3.4 shows the reclassified soils.

Most soils in the district are deficient in available phosphate, have medium to high available potash and low to medium in organic carbon, (Venkateswarlu 2001).

3.2 Crop production

Agriculture, like the rest of India, is the main activity in the district. The main food grains grown include rice , groundnut, jowar and maize. Sugarcane, cotton and a variety of other pulses are also grown. (Government of Andhra Pradesh 2000, Nizamabad District 2001). These crops are grown either under irrigation or rain fed or both. Table 3.1 is the area under irrigation from 1998-99 cropping season to 2000-01 season for the district.

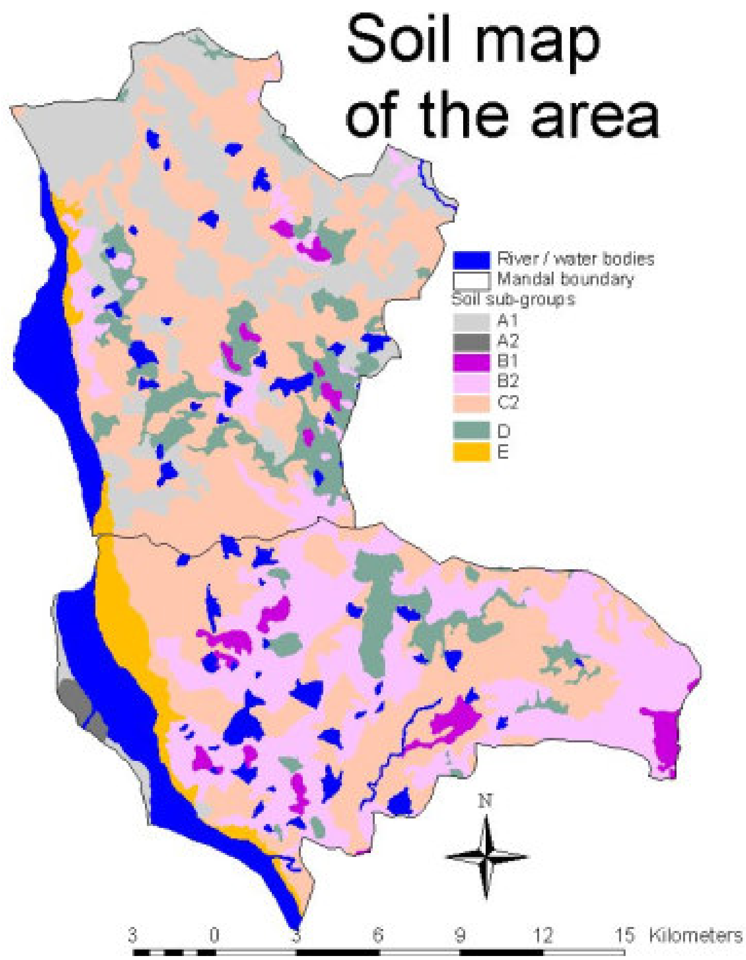


Figure 3.4 Soil sub groups of the area.

The area is characterised by two growing season. The main growing season starting in June lasting until September (Kharif). The main source of water for crop production is the Southwest monsoon. The second growing season starts in December and last until April (Rabi). The main crop grown during this period is rice. Source of water is by irrigation. It is mostly pumped by electrical driven sub-mersible pumps from the ground source. Figure 3.5 shows the relevant cropping calendar.

Table 3.1 Irrigated area under principal crops for three year (area ha).

Crop	1998-99 (ha)	1999-2000 (ha)	2000-2001 (ha)
Paddy	106,000	113,397	127,984
Maize	23,229	26,850	23,605
Tumeric	9,908	10,241	11,297
Sugercane	22,477	22,581	19,357
Groundnut	204	205	142

Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Kharif						Rabi					
South_west Monsoon				North -east monsoon		Winter			Summer		
Kharif (Rainfed/irrigated rice)						Rabi (irrigated rice)					

Figure 3.5 Rice cropping calendar – Nizamabad.

The state of Andhra Pradesh as a whole ranks first in rice production contributing 15 – 18% of the national rice production even though the rice growing area is only 10% of the total rice area of the country. This indicates that rice production in the state is much above the country's average (Government of Andhra Pradesh 2000).

3.3 Materials

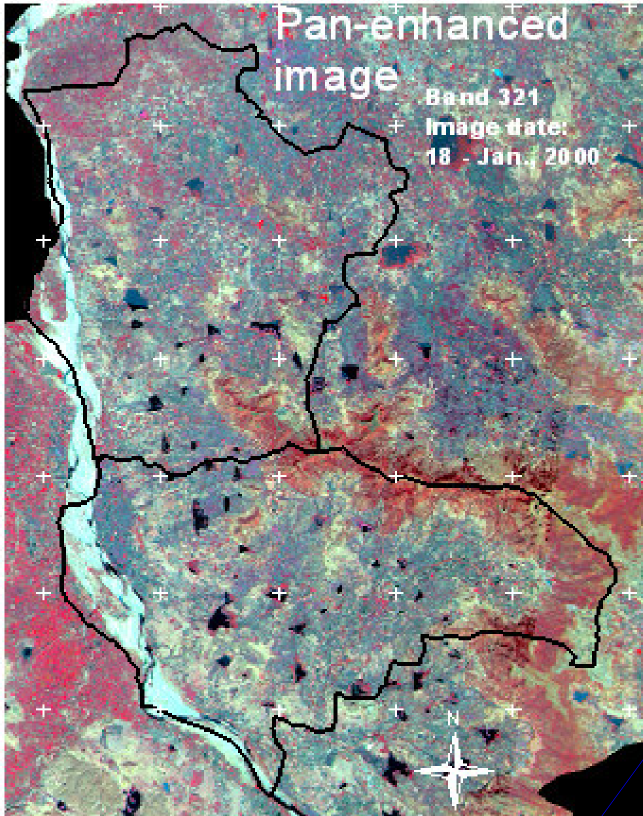
3.3.1 Remote sensing data

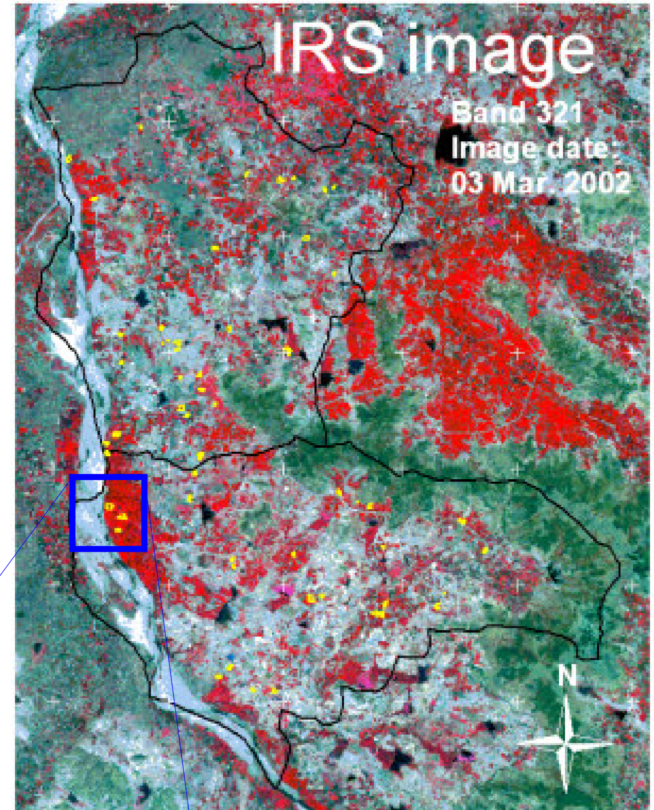
Satellite images used for this study include an IRS image taken on 3rd march 2002 with a spatial resolution of 23m, a pan-enhanced IRS image taken on 18 January 2000 with a spatial resolution of 6m (figure 3.6 and fugure 3.7) and SPOT VGT NDVI dekadal images from April 1998 to April 2002.

IRS images

These are high-resolution multi-spectral images, which made it possible to identify and map out individual farmers' fields. The 23m image was captured by the LISS III sensor aboard the IRS - 1D satellite. The image has four bands, B2 (green), B3 (red), and B4 (NIR) in the visible and near infrared region (0.520 – 0.590µm, 0.620 – 0.680µm, and 0.770 – 0.860µm respectively) and B5 in the short wave infrared (1.550 – 1.700µm). This image was used for the calculation of field level NDVIs.

The other image taken on 18th January 2000 had three bands and was used on hand held computer with GPS to digitise fields. Figure 3.9 shows the hand held computer and the GPS used to digitise farmers fields





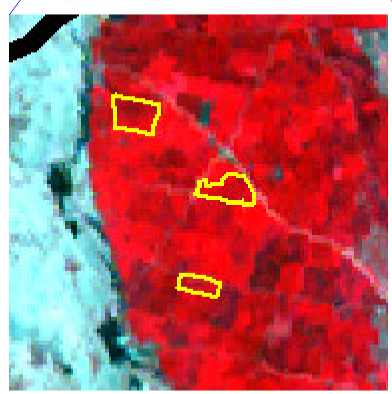


Figure 3.6 18 Jan. 2000 IRS Pan enhanced image used for field digitising.

Figure 3.7 3rd March 2002 IRS image (top) and enlarged part of the image showing fields (left).

SPOT VEGETATION (VGT) images

The VGT sensor was launched in March, 1998 on board of the SPOT 4 satellite, to monitor surface parameters with a frequency of about once a day on global basis at a spatial resolution of 1km. It has four bands; blue (0.430 – 0.470 µm), red (0.61 – 0.68 µm), NIR (0.78 – 0.89 µm) and SWIR (1.550 – 1.750 µm). Unlike the NOAA- AVHRR, the resolution does not degrade with increasing angle of view. The VGT sensor was designed to provide highly accurate geo-referenced images combined with a stable and accurate radiometric calibration. Its layout is better adapted towards terrestrial application like land cover mapping (de Wit & Boogaard 2001).

VGT images are provided in three standard products to users: VGT- P (physical) products, VGT-S1 (daily synthesis products) and VGT S-10 (10 day synthesis products). In this study, the S-10 images were used. The S -10 images represent maximum S-1 values within a 10 day period to minimise the effects of clouds and atmospheric optical depth. Atmospheric corrections for ozone, aerosols and water vapour are done on the images before they are delivered to users (Xiao *et al*. 2002).

A summary of equipment and materials used for data collection and analysis are listed in table 3.2.

Table 3.2 Equipment and materials used during the research.

Equipment	Source/ purpose
Satellite Images	IRS – 18th January 2000 (6 m resolution, pan enhanced) IRS – 03rd March 2002 (23 m resolution) SPOT VGT (Decadal NDVI images April 1998 – March 2002) 1Km resolution
Topographic map	For georeferencing
Hand held computer	For on field digitising of farmers fields
GPS (Global Positioning System)	Positioning and receiving data from satellites for on field digitising with hand held computer
ILWIS, Erdas Imagine, Arc view	GIS software for image processing and analysis
Minitab, SPSS	Statistical software for data analysis
MS Excel	Spreadsheet for data entry and analysis
MS Word	Word processing

3.3.2 Secondary data

Data on land and land use in the form of shape files (geomophological units, water shade, drainage lines and water bodies, soil maps, and communication system and other shape files) and tables (social and climatic data) was made available through the National Remote Sensing Agency of India. This data complemented the field data collected from the farmers.

3.3.3 Research phases

This research was carried out in three phases: preparatory phase, data collection and data analysis phase.

3.3.4 Preparatory phase

This phase involved the formulation of the research proposal in which the research problem, study objectives, research questions and hypothesis were outlined. This was mainly based on literature review and expert knowledge. Then interpretation of the IRS image was done to identify agricultural and non-agricultural areas. The available secondary data on land use, soil and climatic information was studied. The soil was grouped into five practical sub-groups, Rossiter (2002) using the USDA soil classification method (see figure 3.4).

For the major agricultural areas identified the preliminary crop calendars were identified using the SPOT VGT images. The images were classified in ERDAS using unsupervised classification algorithm. The class signatures were visually compared and generalised. The generalised signatures were plotted onto a graph and related to the known crop calenders (details in section 3.3.9).

The 18 January 2000 IRS image was re-projected into UTM (WGS 84) for use with hand held computer for field level digitising. Then a checklist (see appendix 1) was prepared for use during data collection.

3.3.5 Data collection phase

Primary data on land and land use for irrigated rice for the season December 2001 to April 2002 was collected from the farmers through interviews. The interviews were conducted on farmers fields. A check list was used to make sure that all the required information was collected. The first days were mainly used to get familiar with the study area and to pre-test the checklist. Proper adjustments were then made to take into account the encountered biophysical variations.

Figure 3.8 shows an interview in progress and figure 3.9 shows digitising of farmer’s field in progress.

Farmer/field selection criterion was purely random but based on farmers availability. Visits were made to villages and farmers who grew paddy during the rabi 2001 – 2002 cropping season. Fields were visited and interviews were carried out. The field was then digitised using hand held computer and a GPS (figure 3.10 and figure 3.11) with an accuracy of about 7m. A total of 66 farmers were interviewed and their fields were digitised.

Additonal secondary data was collected from agricultural offices and other institutions. The data collection exercise was done during the period between 10th September and 5th October 2002.

3.3.6 Data preparation and analysis

The data extracted from the images and collected from the farmers were entered into a spreadsheet. Interview data was coded and standardised. Nominal and categorical data were normalised into ratio data.

The field polygons from hand held computer were downloaded into a desktop computer and processed to create a database. Figure 3.12 is a flow chart illustrating a summery of the sequence and procedure for data collection to analysis.

Figure 3.8 Interviewing a farmer.

Figure 3.9 Field digitising with a hand held computer connected to a GPS receiver.

Figure 3.10 Hand held computer used to digitise farmers fields.

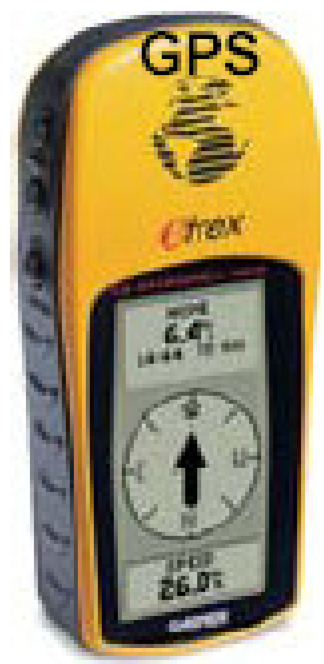


Figure 3.11 Global positioning System (GPS) used in the survey.

Figure 3.12 Flow chart for the study method and data analysis.

3.3.7 NDVI Extraction

The choice of the date of the IRS image with a resolution of 23m taken on 03rd March 2002 was based on the analysis of the information given by the farmers on the date of transplanting and date of harvesting which gave the general crop calendar for the 2001 – 2002 Rabi crop. The choice of the date was in such away that the image should coincide with the peak vegetation period of most of the farmers fields. The image was processed in a GIS environment and an NDVI map was generated using band 3 (NIR) and band 2 (red) of the IRS image by applying the formulae:

$$NDVI = (Band\ 3 - Band\ 2)/(Band\ 3 + Band\ 2)$$

The field polygons were imported into ILWIS. The polygons were then rasterised and field level NDVIs were generated by crossing the field raster images with the NDVI image. These were then aggregated using an aggregation algorithm. The aggregation was done by either the maximum NDVI, the average NDVI or the median.

3.3.8 Validation of Field NDVI

There were differences from farmer to farmer in responding to the interviews. This resulted in differences in the quality of the information. To make sure that the data was uniform, each inteview was rated. The quality ratings were later used in the anlysis as weighing factors to standardise the data.

In view of this, field level NDVIs from the IRS image were evaluated and validated for rice existence during the 2001 – 2002 Rabi cropping season. This was done through identifying bare areas and water bodies, and comparing these NDVIs with those of the fields. All fields with NDVIs equal to or less than bare soil NDVIs were removed from the list. Then the field polygons were finally over laid on a false colour composite image (Band 3 2 1). Fields that were on areas that did not indicate possible existence of vegetation were identified and also removed from the list regardless of their NDVI value. Figure 3.13 is an example of fields that did not have any signs of rice (figure 3.13c and figure 3.13d) and that were removed for further analysis. Figures 3.11(a and b) show fields that had rice. Out of the 66 fields surveyed, 55 fields were found to have valid rice as per their NDVI value confirmed by the 03 march 2002 IRS false colour image.

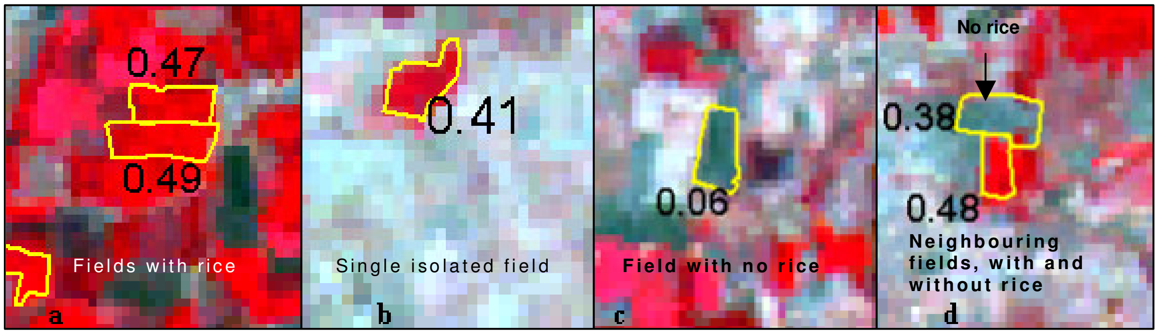


Figure 3.13 Field level NDVI validation and selection.

(The numbers represent maximum NDVI of the fields)

3.3.9 SPOT VGT NDVI

The image for the first decade of March was used to extract individual VGT pixels. The NDVI values indicated the density of the cropped fields in the 1km pixel because during this period green vegetation contributing to high vegetation reflectance mainly came from irrigated crops. These NDVIs were considered as cropping intensity indicators, because they indicated the degree of cropping intensity in each pixel. Therefore, for the purpose of this research they were regarded as cropping intensity index for each pixel.

The image was exported into ILWIS software and the NDVI values were then scaled from the values between 0 and 255 as provided by the VGT images to values between – 0.1 to + 0.92 using the formulae;

$$\text{Real NDVI(VGT)} = (0.004 \times \text{VGT value}) - 0.1$$

Where;

Real NDVI (VGT) = NDVI values between -0.1 and +0.92
VGT value = SPOT VGT NDVI values between 0 – 255.

This was done for easy comparison with the values from IRS image. Figure 3.14(a) is the scaled VGT NDVI image and Figure 3.14 (b) is a classified cropping intensity image of the first decade of March 2002. The classification was done based on the ploted graphs for vegetation intensity. The pixels with high NDVI were define as indicating the availability of vegetation through comparing with the time series VGT images as explained in section 3.3.1 and the high resolution image. Four categories of vegetation availability were identified as high cropping intensity (High), medium cropping intensity (Medium), low cropping intensity (Low) and very low cropping intensity (Very low). This classification visually corresponded very well with the IRS image for March 3, 2002. Fugure 3.14 and figure 3.15 show the images. Indicating exactly where rice was grown.

The availability of the time series VGT images (from 1998 – 2002) also enabled the production of NDVI curves for different vegetation and cropping pattern for the study area showing the development of vegetation over the year. Figure 3.16 is a graphical representation of vegetation development and cropping intensity for the 2001 – 2002 cropping season.

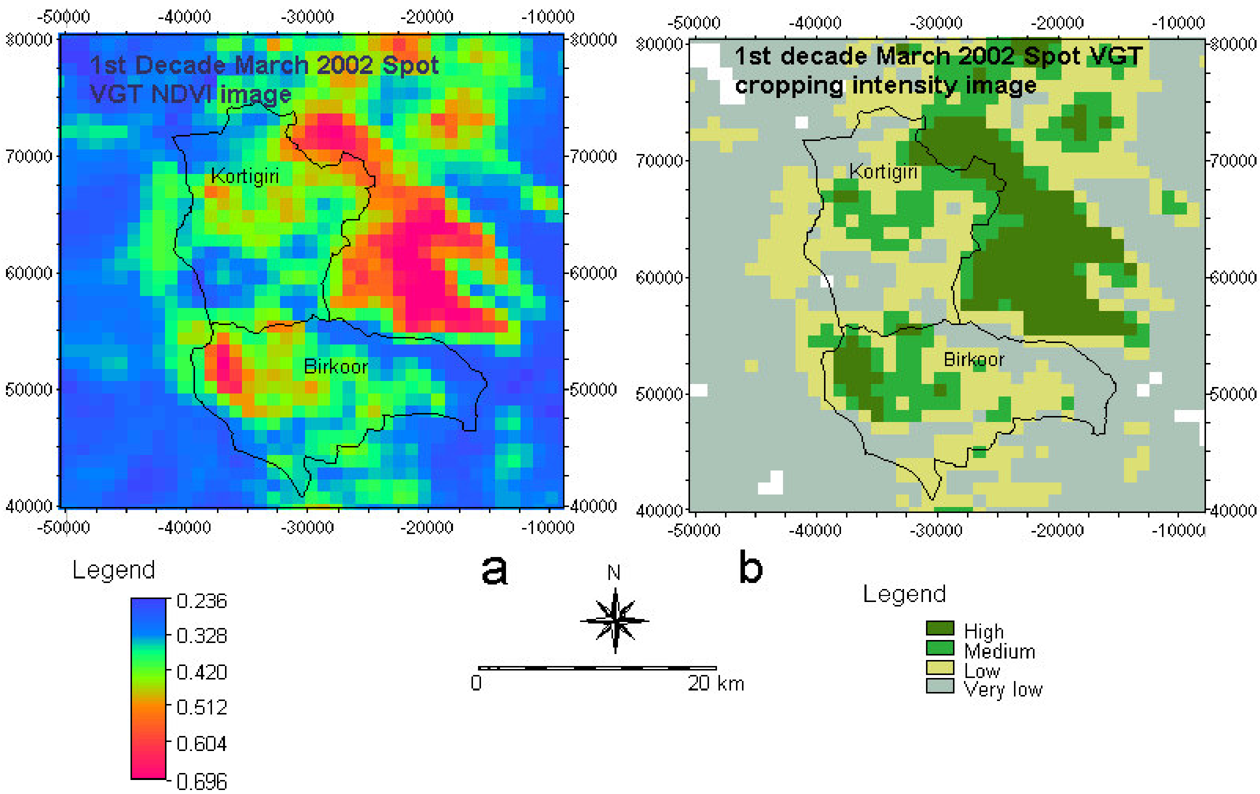


Figure 3.14 Pseudo colour VGT NDVI image (a) and a classified cropping intensity image (b).

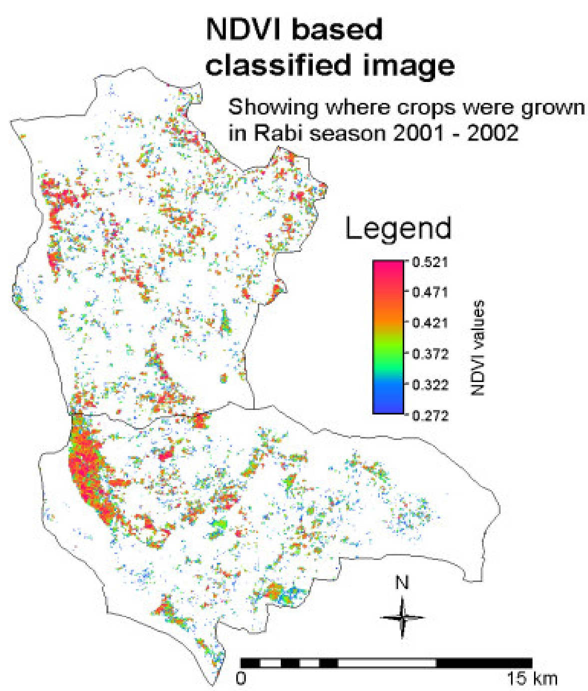


Figure 3.15 IRS NDVI image showing areas of high agricultural activities.

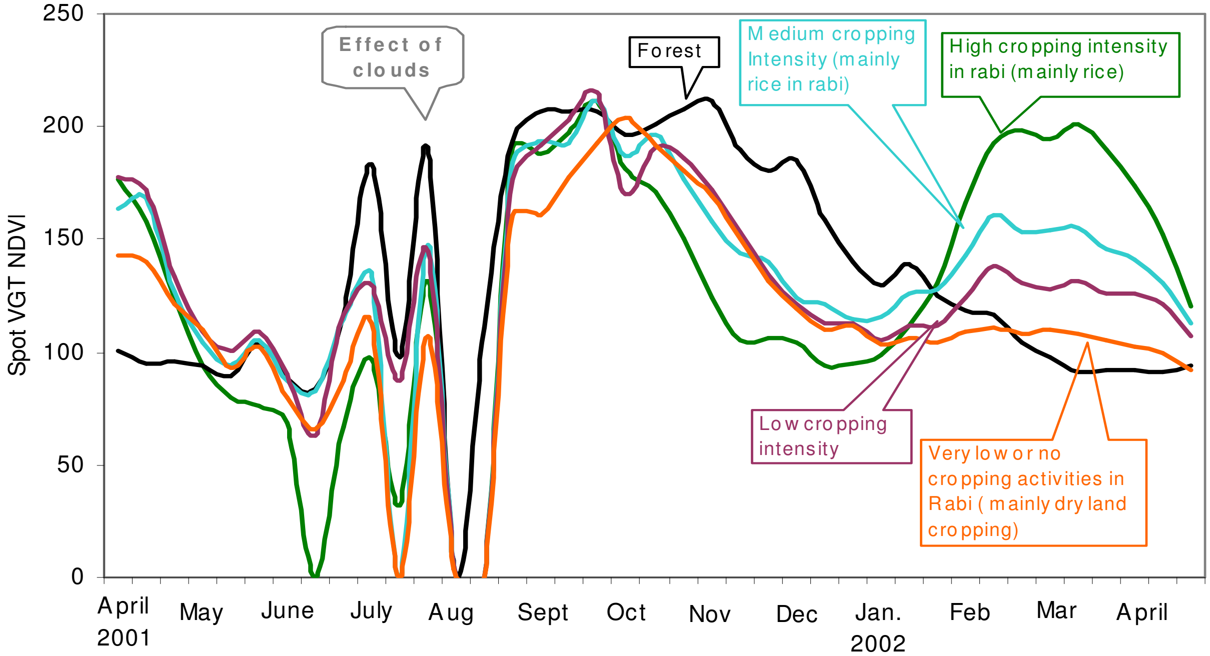


Figure 3.16 SPOT VGT NDVI curves for the 2001 - 2002 growing season.

3.3.10 Testing for Normality and statistical analysis

All the data was entered into a spreadsheet for analysis. Before the data was subjected to statistical analysis, it was tested for normality to determine the best distribution for analysing the data. Then the data was statistically analysed.

The first step in the analysis was to establish the relationship between NDVIs and yield data at field level. Secondly, land and management parameters were compared with yields and NDVIs. Then through multiple regression the relationships were further tested to establish a yield prediction model to predict field level yield.

4 Descriptive statistics

Data on land and management practices to grow rice during the Rabi season 2001 – 2002 and the respective yield data were collected from farmers through interviews. Data units as reported by farmers were converted into standard metric (S.I.) units. The IRS satellite image of 3rd March 2002 provided the field level NDVI data. The total sample size for this study consisted of 55 valid fields.

Parametric statistical analysis techniques require data to be distributed normally. Means and standard deviations are useful to describe data but become poor when the data are not normally distributed. Histograms, stem-and-leaf plots and box plots can also be used to visualise data. They help to show their distribution characteristics.

4.1 Testing the distribution of yield data

The yields from the surveyed fields ranged from 2595 to 8649 kg/ha with a mean of 6522 kg/ha and median of 6919kg/ha. Figure 4.1 (a) shows a histogram fitted with a normal curve and figure 4.1 (b) shows Z-scores of the 55 yield data. The data seem to follow a normal distribution. Testing for normality by the two tailed Kolmogorov-Smirnov test gave a p value of 0.31 which confirms the hypothesis that the data is normally distributed, therefore parametric analysis techniques can be employed for further analysis without fulfilling any transformation requirement.

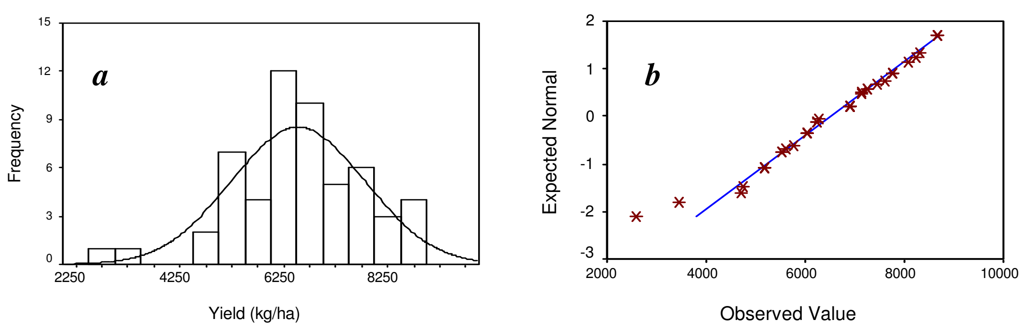


Figure 4.1 Histogram fitted with a normal probability curve (a) and Z-score for (b) farmers' yields.

4.2 NDVI versus field level yield data

Of the field level NDVI calculated from the IRS image, maximum, average (mean) and median were obtained for each field. The NDVIs were then correlated to the yield data and it was found that maximum, median and mean NDVIs were significantly correlated to yield ($p = 0.00$, $p = 0.002$ and $p = 0.003$ for maximum, median and mean NDVI respectively) with correlation coefficients of $r = 0.520$, $r = 0.401$ and $r = 0.393$ for maximum, median and mean NDVI respectively.

Figure 4.2 shows the result of scatter plots for two NDVIs fitted with a logarithmic regression line with the following equations: Y = 10167 + 4431Ln(maximum NDVI) and Y = 8772 + 2029Ln(mean NDVI). The results suggest that there is a significant relationship between yield and maximum NDVI ($R^2_{adj} = 25\%$, $p = 0.00$) and mean NDVI ($R^2_{adj} = 14\%$, $p = 0.003$). The maximum NDVI proved to be the better explanatory of the two.

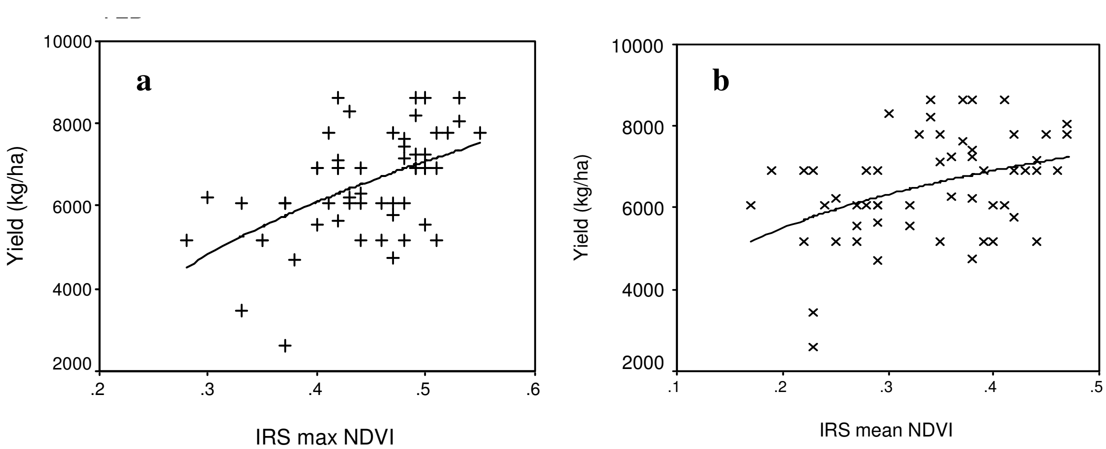


Figure 4.2 Scatter plot for yield against NDVI fitted with a regression line.

Linear transformation and various combination proved not to improve the relationship

4.3 The effect of land parameters on yield and NDVI

4.3.1 Relationship between yield, NDVI and soil sub-groups

Soil plays a major role in crop production. It is a medium for water and nutrient supply to crops. Its natural characteristics determine the availability and supply of these resources to the crop.

Table 4.1 shows the distribution of yield and NDVI by soil sub-group. The table and box plots (figure 4.3) indicate that the highest yield, NDVI and cropping intensity is in soil sub group E. Most of the sample fields were in soil sub-group C2, and the least samples in sub-group A1. This bias in sampling frequency relates to the extent each sub-group occur (see map 3.4).

Table 4.1 The distribution of yield and NDVI by soil sub-group.

Soil Type	Count	Cropping intensity index	Average IRS Mean NDVI	Average Max. NDVI	Average Yield (kg/ha)
A1	4	0.335	0.268	0.420	6357
B2	6	0.392	0.370	0.483	6463
C2	33	0.354	0.333	0.435	6361
D	5	0.346	0.298	0.408	5669
E	7	0.489	0.414	0.490	8031
Total	55	0.372	0.339	0.442	6522

The box plots, figure 4.3(a), show the distribution of yield in different soil sub-groups. The box plots suggest more variation in soil sub-group D and least in sub-group E. Testing for differences in mean yield by soils suggested that at least one soil sub-group is significantly different from other soil sub-groups (ANOVA $p = 0.01$).

A step-wise forward regression analysis with all soil sub-groups showed that yields from soil E are significantly different from yields from other soil sub-groups and explains 19.0% (R^2_{adj}) of the yield variability ($p = 0.001$).

Figure 4.3(b) and 4.3 (c), show the distribution of NDVIs by soil sub-group. The box plots suggest more variation in NDVI in soil sub-group C2 than the other soil sub-groups. The variation is much less in soil sub-group E and A1. It also suggests lower average NDVI values in soil-subgroups A1 and D.

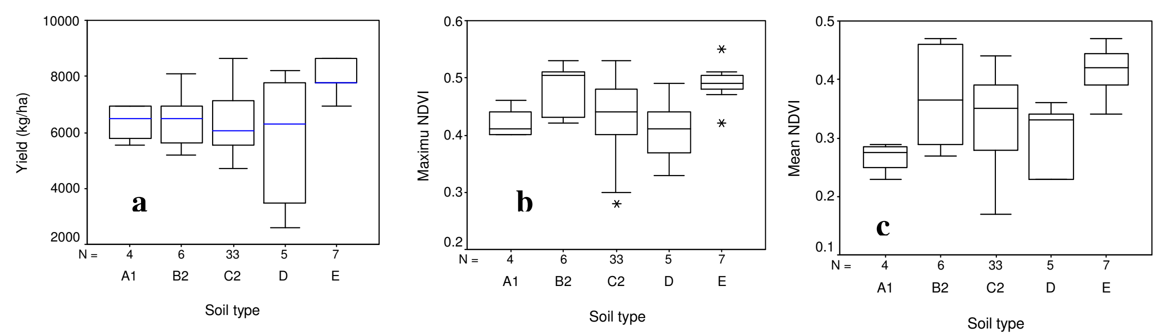


Figure 4.3 Box plots showing the relationship of yield and NDVIs by soil sub-group.

A test to find if there is significant difference between mean NDVI from different soil sub-groups indicated that there is significant difference in NDVIs due to differences in soil sub-groups (ANOVA $p = 0.004$ and 0.001 for maximum and mean NDVI respectively). These results suggest that soil has a significant impact on growth and condition of rice, which can be measured through remotely sensed NDVI.

Stepwise forward regression analysis revealed that NDVI from soil sub-group E and B2 is significantly different (R^2_{adj} = 12.3%) from the other sub-groups (p = 0.01 for soil E and p = 0.04 for soil B2) for maximum NDVI. Using mean NDVI only soil E significantly explains 12.0% of the mean NDVI variability (p = 0.006). The regression relationship is given by;

$$NDVImax = 0.430 + 0.0595(Soil\ E) + 0.0529(Soil\ B2)$$
$$NDVImean = 0.329 + 0.0857(Soil\ E)$$

The combined effects of NDVI and soil on yields are tested in chapter 5.

Testing whether the geomophological units have effect on yield and NDVI, ANOVA showed that there is no significant difference in yield and NDVIs due to differences in geomophological units (p = 0.83 and 0.77 for yield and NDVI respectively).

4.3.2 Effect of soil on cropping intensity

A test to find if there is significant difference between cropping intensity by soil was done. Figure 4.4 is a box plot showing the distribution and extent of cropping intensity by soil.

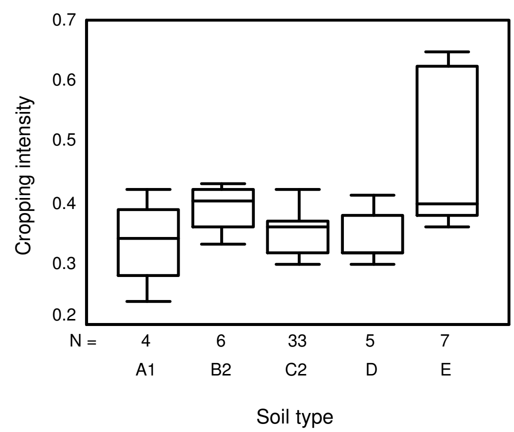


Figure 4.4 Distribution of cropping intensity in different soil sub-groups.

The box plot suggests great variation in cropping intensity within and between soil sub-groups. With soil sub-group E suggesting to have greatest cropping intensity variation within the group. However, the mean NDVI value is higher than the mean NDVIs from other soil sub-groups (see also table 4.1). Soil C2 has the lowest variation in in cropping intensity. The box plot suggests that the cropping intensity in soil A1, C2 and D are not significantly different.

A test to find if there is significant difference between cropping intensities proved that there is significant difference in cropping intensity in different soils (ANOVA p = 0.00), suggesting that soil has an effect on cropping intensity.

A stepwise regression analysis to identify which of the soils significantly explain the cropping intensity variability showed that soil sub-group E has significantly different cropping intensity and explains 34.4% (R^2_{adj}) of the cropping intensity variability (p = 0.00)

4.3.3 Effect of cropping intensity on yield

A test was done to find the relationship between cropping intensity and yield. Figure 4.5 shows the result of a scatter plot for cropping intensity versus yield fitted with a logarithimic regression line with the following equation: Y = 9228 + 2700Ln(Cropping intensity index). The results suggest that there is a significant relationship between yield and cropping intensity (R^2_{adj} = 12%, p = 0.006).

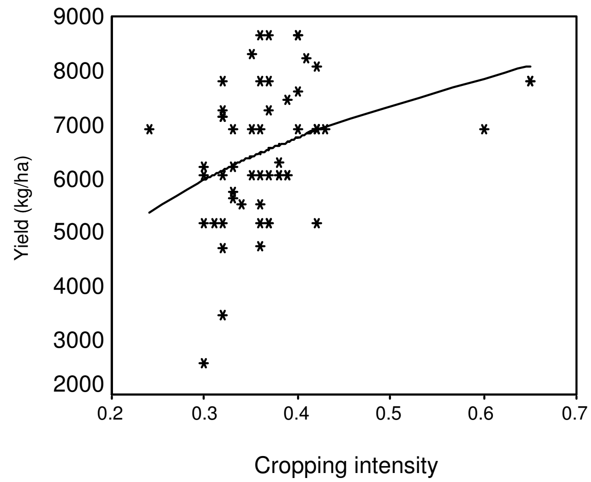


Figure 4.5 Effect of cropping intensity on yield.

At present one must conclude that soil, cropping intensity and NDVIs are related, and that all are showing a similar impact pattern on yield. They are mutually exchangeable in yields estimation model. (see chapter 5). The intensity index has a draw-back that it is not field specific nor constant over years.

4.4 The effect of Management on yield

Farmers apply different management practices to get reasonable yields from their plots and they operate at different technological levels. Data on operation sequence that was followed by individual farmers was collected and analysed. The data included all levels of technological operations and production level practiced in the area.

Figure 4.6 shows the operation sequence of Rabi rice production in the study area during the 2001 – 2002 growing season.

Management operations as reported by farmers were screened based on the date of the image. All operations before this date were analysed to find their effect on the final yield and NDVI.

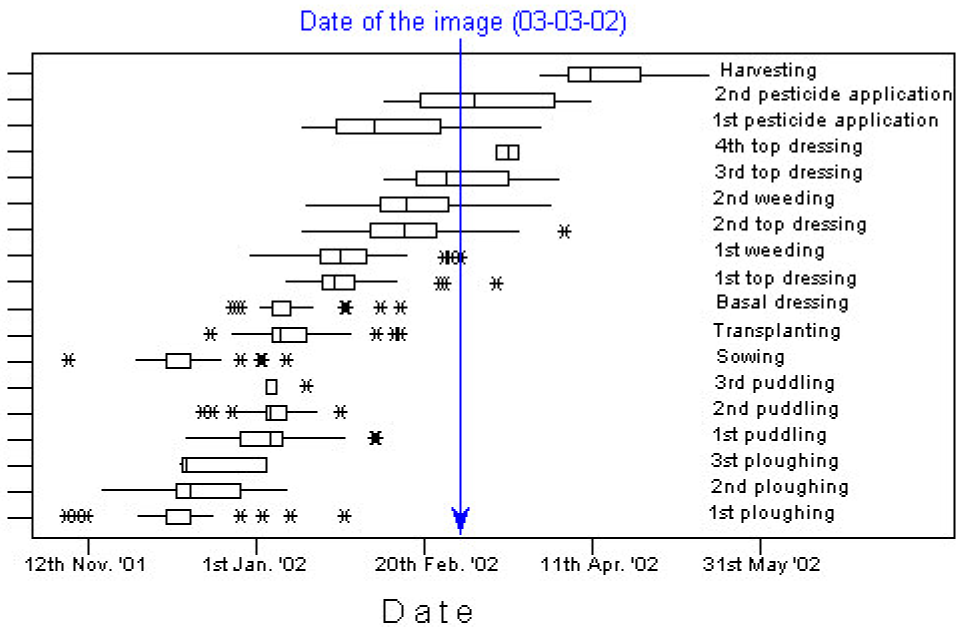


Figure 4.6 Rabi rice management operations in Nizamabad.

4.4.1 Varieties grown

The varieties grown are mainly improved varieties. Table 4.2 shows the mean yield of the varieties. The commonest variety was MTU 1010 (37x), Other varieties were BPT 5024 (5x), Eramallelu (3x), Tellahamsa (6x), IR64 (1x), JGL (1x) and M7 (2x). ANOVA showed that there was no significant yield and NDVI difference between varieties (p = 0.32 and 0.50 respectively).

Table 4.2 Varieties grown during the 2001-2002 Rabi season.

Variety	Count	Mean Yield	Growing period (days)
BPT5024	5	5842	145
Eramallelu	3	6544	120
IR64	1	7150	120
Jegthayal (JGL)	1	7127	-
M7	2	3892	-
MTU 1010	37	6693	140
Terra Hamsa	6	6688	125
TOTAL	**55**	**6522**	

4.4.2 Ploughing

Ploughing starts early December. 8 farmers did their 1st ploughing in November and 4 farmers in January. Few farmers ploughed once (8x), many ploughed twice (42x) and others thrice (5x). ANOVA testing to find if there is a difference in mean yield and NDVI due to differences in number of ploughings showed that there in no significant difference in yield (p = 0.36) and NDVI (p = 0.18).

Puddling is done just before transplanting. 22 farmers had their fields puddled once, 24 farmers puddled twice and 9 puddled thrice. ANOVA showed that there is no significant difference in yield (p = 0.13) and maximum NDVI (p = 0.24) due to differences in number of puddlings.

Ploughing and puddling was done by either tractors or animals. Only 3 farmers used animals to plough and 2 farmers used animals to puddle. Analysis to find if ploughing and puddling methods contribute to differences in yield and maximum NDVI was not done because the number of cases were too few for statistical analysis and to make valid conclusions.

4.4.3 Date of transplanting

Paddy rice is mainly transplanted when the seedlings are about 30 days old, sowing was mostly done in December. Transplanting dates ranged from as early as 17^{th} December 2001 to 11^{th} February 2002 with most farmers transplanting in the first and second week of January (see figure 4.6).

Transplanting time in each field depended on the availability of labour. Most of the transplanting was done within one day (by hand). Figure 4.7 shows the scatter plots for yield and NDVI against date of transplanting. The fitted regression line shows that planting date has a significant effect on yield and NDVI ($p = 0.03$ and $p = 0.01$), explaining 6.8 % and 16.4% (R^2_{adj}) of the total yield and maximum NDVI variability respectively. Mean NDVI could not significantly explain variability due to planting date ($p = 0.13$). The regression lines are explained by the following equations:

Yield (kg/ha) = 1309800 - 35 (transplanting date);

maximum NDVI = 91 - 0.0024 (transplanting date).

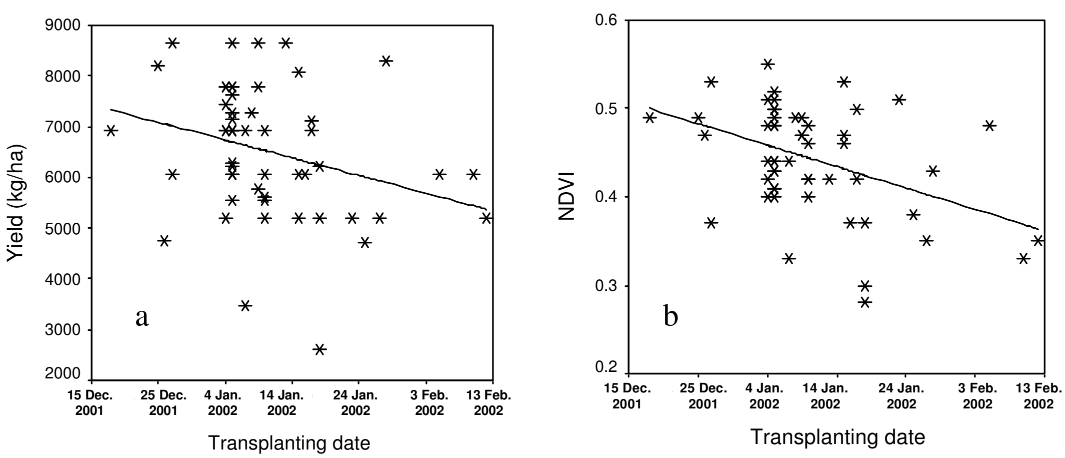


Figure 4.7 Scatter plot fitted with a regression line.

4.4.4 Fertiliser application

All farmers applied nitrogen fertiliser in the form of Urea (except one who used sulphate of ammonia as second application) and compound fertiliser in the form of 20:20:0, 19:19:19, 17:17:17, DAP, 12:32:18 or 14:28:28. The fertilisers were applied in splits of two to four and the last application (regardless of number of splits) was mainly urea with potassium (MOP) combination. In this analysis only those applications done before the date of the image, 3rd March 2002, were considered for analysis. At this date an average of 247kg/ha (114kg N/ha) of Urea was applied and compound fertilisers at an average of 397 kg/ha. Only 13 farmers had applied potassium fertiliser at an average of 90 kg/ha and 14 applied Zinc in the form of either Zinc sulphate or in combination with other micronutrients at an average of 30 kg/ha.

Correlations of amount and type of fertiliser applied and yield and NDVI were very poor as shown in table 4.3. Only the correlation between zinc and Yield, though very weak, was significant ($p = 0.04$) with a correlation coefficient $r = 0.274$.

Table 4.3 Correlation of Yield, NDVI and type of fertiliser applied.

Fertiliser type		YLD	Max NDVI	Mean NDVI
Urea	Correlation	0.062	0.057	0.107
	P	0.653	0.680	0.442
Compound fertiliser	Correlation	0.005	-0.114	0.070
	P	0.973	0.406	0.611
Potassium fertiliser	Correlation	0.550	0.015	0.119
	P	0.689	0.911	0.389
Zinc	Correlation	0.274	0.110	-0.050
	P	0.042	0.425	0.717

Analysis for Zinc showed a yield increase factor of 24kg/ha if Zn is applied in one form or another. It explained 5.8% (R^2_{adj}) of yield variability ($p = 0.04$). The response of yield to the application of Zinc shows that most soils are low in available micronutrients especially Zinc, agreeing with what Venkateswarlu (2001) and Rao *et al.* (1995) reported.

Some farmers applied Zinc as basal dressing, others with the first top dressing and others as second top dressing. Analysis to find which of these had significant effect revealed that Zinc applied as basal dressing was significant, accounting for 7.1% (R^2_{adj}) of the yield variability ($p = 0.03$).

Analysis to find the effect of Zinc on NDVI showed no relationship.

4.4.5 Number of fertiliser applications.

Figure 4.8 is a box plot showing the effect of fertiliser application frequency on yield. The box plot suggests more yield if fertiliser was applied at least 3 times.

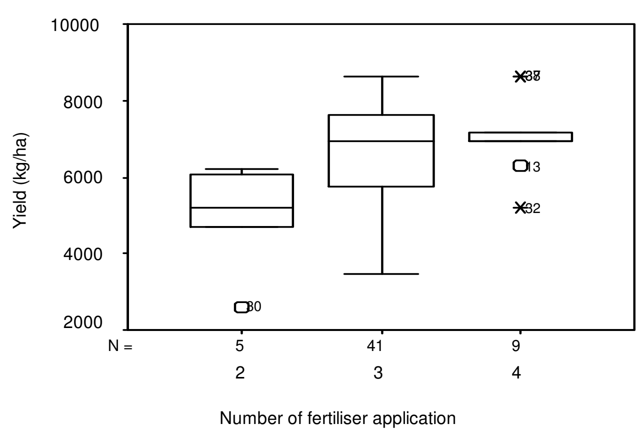


Figure 4.8 Effect of fertiliser application frequency on Yield.

Testing to find if there is a significant difference in yield, ANOVA suggested that the number of fertiliser applications relates to the yield variability between fields (ANOVA $p = 0.007$).

A stepwise regression indicated that number of fertiliser application accounts for 13.5% of the yield variability ($p = 0.003$, $R^2_{adj} = 13.5\%$). The regression relationship is give as; $Y_{(kg/ha)} = 6678.20 - 1723.40$(if only two split applications).

Analysis to find which nutrient is responsible for this effect failed to isolate a single nutrient as being responsible for this effect on yield, suggesting that it is a combined effect of the nutrients applied over the two splits. It also suggest that there will be a deficiency of nutrients at later stages of the growth cycle if only two splits are done. This agrees with Rao *et al.* (1995) who observed that applying urea in 3 splits gave the highest yields.

Detailed analysis of nutrients applied at certain dates versus yields also turned out an impossible exercise. The variability was too high. Farmers clearly do not follow a standard fertiliser application scheme that seem now a concern.

Soil in the study area are classified as having high phosphorus and potasium content (Rao et al., 1995; Venkateswarlu, 2001) which suggest that application of these nutrient bring nutrient imbalance. This could be one of the reasons of the nonsignificant relationships tested between N:P:K application timings and yield.

Figure 4.9 shows the relationship between maximum NDVI (a) and mean NDVI (b) versus frequency of fertiliser application. The box plots suggest low NDVI values with only two applications. It also suggest high variability in NDVI, with these applications. ANOVA suggested that the variations in NDVIs can significantly be explained by the number of fertiliser applications done in irrigated rice ($p = 0.01$) if maximum NDVI is considered. Analysis suggested that neither median nor mean NDVI can significantly explain the NDVI variability ($p = 0.11$ and 0.15 respectively).

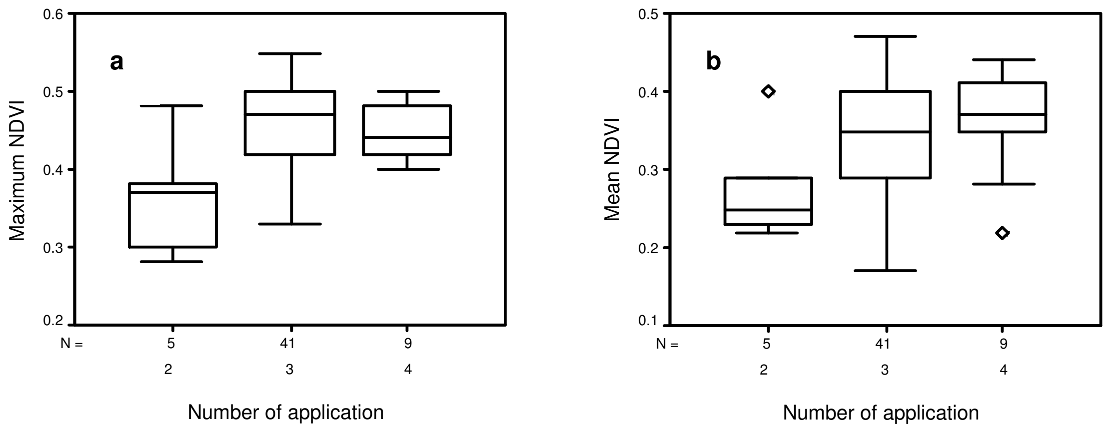


Figure 4.9 Effect of fertiliser application frequency on NDVI.

A stepwise multiple regression showed that NDVI is significantly low if two application are done explaining 16.5% (R^2_{adj}) of the NDVI variability between fields (p = 0.00), with the regression relationship; $NDVI_{max} = 0.452 - 0.09$(if only two split applications).

4.4.6 Basal dressing

Box plots in figure 4.10 show the distribution and effect of basal fertiliser application on yield , maximum NDVI and mean NDVI. 45 farmers applied basal fertiliser and 10 did not. The box plots suggest that there is no significant difference between fields that had a basal fertiliser dressing and those that did not. ANOVA confirmed this.

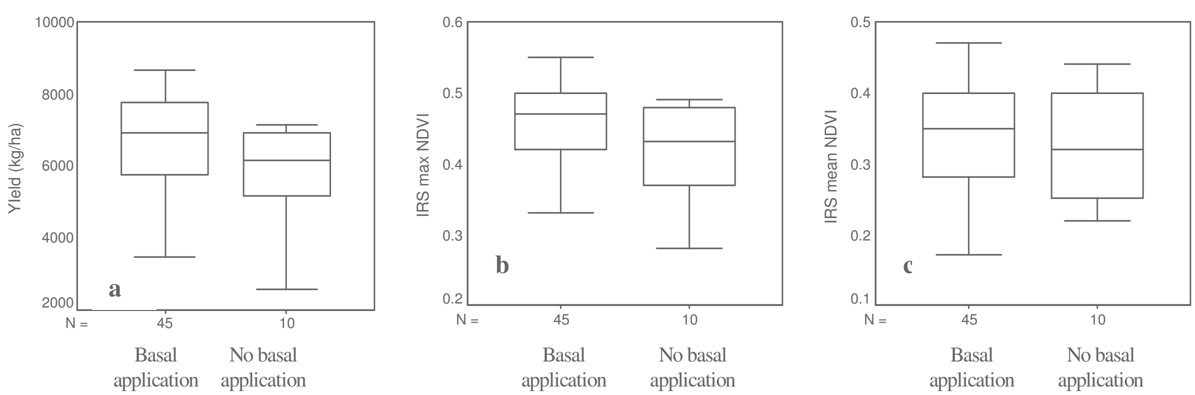


Figure 4.10 Basal fertiliser application versus Yield (a), maximum NDVI (b) and mean NDVI (c).

4.4.7 Irrigation

Irrigation water supply is a major production factor. The power problem as expressed by farmers affected the supply of water in most of the fields at different times of growth. Most farmers had one irrigation pump supplying water to an average area of 1.83ha within a period of the 9 hours of power supply per day. This resulted often in an insufficient water supply. Power or pump breakdowns causes an irregular water supply resulting in severe water shortages at certain stages of rice growth .

Table 4.4 shows the mean yield and NDVI for the water regimes as expressed by farmers. Box plots (figure 4.11) show the effect of water and distribution on yield and NDVI for each water regime.

Table 4.4 Effect of water supply on yield and NDVI.

Time of water shortage	Count	Average Yield (kg/ha)	Average maximum NDVI	Average mean NDVI
Flowering	11	5916	0.4291	0.3291
Irregular supply	16	5879	0.4325	0.3334
No shortage	28	7127	0.4561	0.3468

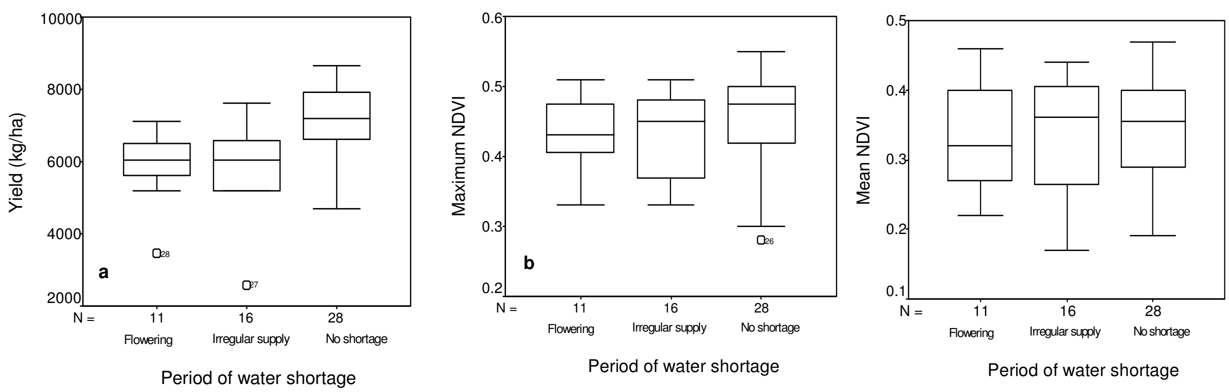


Figure 4.11 Impact of irrigation frequency on yield and NDVI.

ANOVA showed that the availability of water in paddies has a significant effect on yield (ANOVA $p = 0.00$), but showed no significant effect on NDVI (ANOVA $p = 0.33$ and 0.78 for maximum and mean NDVI respectively).

Stepwise regression analysis for yield with each water regime as a variable (after normalising, with 1 or 0 as parameters) resulted in the relationship: Yield = 5894 +1232 (if no water shortage), $R^2_{adj} = 22.0\%$ ($p = 0.00$) with a very high significant regression coefficient.

4.4.8 Depth of irrigation during fertiliser application

The level of water in paddies during fertiliser application has a significant effect on fertiliser utilisation by crop. Ideally fertilisers should be applied when there is minimal water in fields (just moist enough to allow dissolving) and the level to be incresed within 24 – 48 hours to incorporate the applied fertiliser into the rooting zone where plants can absorb it. However, some farmers applied fertiliser in fully flooded paddies.

Analysis to test the effect of water level during fertiliser application showed that there is no significant impact on yield and NDVI ($p = 0.69$ and 0.18 for yield and maximum NDVI respectively).

4.4.9 Weeding

Most of the farmers did weeding twice by the time the image was taken. Most of them indicated that weeds are not a serious problem during the Rabi season. However, ANOVA showed that there is significant difference in yields between farmers who weeded once and those who weeded twice ($p = 0.01$) and failed to show significant differences in NDVI ($p = 0.17$).

Regression analysis showed that weeding twice is associated with lower yields explaining 12.5% (R^2_{adj}) of the variability with a regression relationship; Yield (kg/ha) = 7179 - 1005(if weeded twice) ($p = 0.01$).

The second weeding was done by hand in all fields that had second weeding. It was done between the 40th and 60th day after transplanting, coinciding with the reproduction phase of rice (see figure 2.6). This suggest that weeding caused damage during the reproduction phase resulting in lower yields.

4.4.10 Pest and diseases

Farmers explained that diseases are not a real problem during Rabi season due to the lower relative humidity as compared to the Kharif season. Pesticides and fungicides were applied as a preventive measure. Still, few farmers experienced pest and desease attacks in their fields. The pests reported were brown plant hopper (4x), Stem borrers (7x), leaf folders (3x) and rats (2x). Correlation between pests and diseases versus yield and NDVI could not result in significant relationships for lack of number of observations.

4.5 Summary of relevant findings

It is envisaged in this analysis that not all the parameters affecting yield and NDVI at field level have been exhausted. Factors like ground water level and quality (since irrigation depends on ground water in the area) has not been explored to find its effect on yield and NDVI due to insufficient data available for this analysis.

In the analysis some parameters have been found to explain yield and NDVI variability. Summary of the parameters that turn out to be significant is as follows:

Yield = *f*(NDVI, soil type, cropping intensity, transplanting date, number of fertiliser Applications, Zinc application, availability of water, weeding method).

NDVI = *f*(soil type, date of transplanting, number of fertiliser applications).

5 Multiple regression – Model development

Chapter 4 explored the relationships and effects of land and management aspects on yield and NDVI. Some land and management parameters had a significant effect on yield and NDVI. This chapter explored and established a yield prediction model based on NDVI and significant land and management parameters.

Stepwise forward Multiple linear regression was applied to build the model. This selected only those parameters that strongly and significantly explained yield variability. Stepwise forward regression adds variables to a regression model for the purpose of identifying a useful subset of predictors. Repeated 'trial and error' attempts were done to identify interactions between parameters and to explore unexpected sign of coefficients.

Eight samples were randomly selected from the yield data and reserved for model testing. Multiple regression was then applied to the remaining set of data. All the regression models were weighted by a quality weighing factor as explained in section 3.3.8 to standardise the data.

5.1 NDVI prediction using land and management parameters

All the significant variables were entered into the stepwise multiple regression to select the best subset that explains the field level NDVI variability. Through repeated trial and error, 3 variables were selected as predictors explaining 21.0% (R^2_{adj}) of NDVI variability. The purpose of this was to identify which parameters can explain the NDVI variability to avoid autocorralation when building the final model. The regression equation is:

$$\text{NDVI max} = 0.4603 - 0.0020(\text{DOTJ}) + 0.0435(\text{Soil\_E}) + 0.0437(\text{Soil\_B2})$$

Where;	NDVImax	= Predicted field level maximum NDVI
	DOTJ	= date of transplanting (day of the year from Jan. 1, 2002)
	Soil_E	= if rice is grown on soil sub-group E
	Soil B2	= if rice is grown on soil sub-group B2

The model suggests a negative effect on NDVI with delayed planting and that high NDVI values will be obtained if rice is grown in soil sub-groups E and B2. Table 5.1 shows the coefficients, t-values and p-values for each predictor in the model. The date of transplanting cross-relates between NDVI and yield data.

Table 5.1 Coefficients and p-values for NDVI prediction model.

Constant = 0.4603	R^2_{adj} = 21.0%		
Predictor	**Coefficient**	**t**	**p**
Date of transplanting	-0.0020	-2.7	0.01
If soil sub-group E	0.0435	2.1	0.05
If soil sub-group B2	0.0437	2.0	0.56

5.2 Integrated Yield prediction model

The final stage was to built an integrated yield prediction model based on NDVI, land and management factors.

First, was to establish a yield prediction model without NDVI for later comparison. All the management and land variables that were significant were entered into the multiple regression. The best selected predictors explained 38.1% (R^2_{adj}) of the yield variability in the area. The regression equation is given below;

Yield = 6046 + 1142(**Soil_E**) + 962(**WS_NS**) -1370(**APP_2**)

Where: Yield = yield (kg/ha) predicted by land and management factors
Soil_E = Soil sub-group E
WS_NS = If there is no water shortage
APP_2 = if fertiliser is applied only twice

The results suggest that if land and magement factors are considered for yield prediction, 38.1% of the yield variability will be explained by the model. Table 5.2 shows the coefficients, t-values and probability level of the predictors.

Table 5.2 Yield prediction model using Land and management factors.

Predictor	**Coefficient**	**t**	**p**
Constant = 6046	R^2_{adj} = 38.1%		
If soil sub-group E	1142	2.7	0.01
If no water shortage	962	3.2	0.00
If fertiliser is applied only twice	-1370	-2.4	0.02

The final yield prediction model was done by entering NDVI values and all the significant variables that were not related to NDVI prediction into a stepwise multiple regression to select the best subset that explains significantly yield variability at field level. The model selected four variables, explaining 45.8% of the variability. These four predictors provided better results than any other combination. The model is defined by;

Yield = 3027 + 7751(**$NDVI_{max}$**) + 1030(**WS_NS**)– 648(**WM2_H**) – 1126(**APP_2**)

Where: Yield = Predicted yield (kg/ha)
$NDVI_{max}$ = field level NDVI aggregated by maximum
WS_NS = if there is no water shortage
WM2_H = second weeding if done by hand weeding

APP_2 = if fertiliser is applied only twice instead of three or more

Table 5.3 shows the results of the model.

Table 5.3 Yield prediction model using NDVI, management and Land.

Predictor	**Coefficients**	**t**	**p**
Constant = 3027,	$R^2_{adj} = 45.8\%$		
NDVI	7751	2.9	0.01
If no water shortage	1030	3.8	0.00
If second weeding is done by hand	- 648	-2.3	0.02
If fertiliser is applied only twice	-1126	-2.0	0.06

Figure 5.1 shows a scatter diagram of the relationship between predicted yield from the independent data against reported yield and all the data agaist reported yield. Fitted with a regression line of all the samples. The line explains 12.4% of the yield variability ($p = 0.01$) with a regression equation $Y_{pred} = 5891 + 0.24$(reported yield).

Table 5.4 shows the results of the predicted yields from the 8 randomly selected samples.

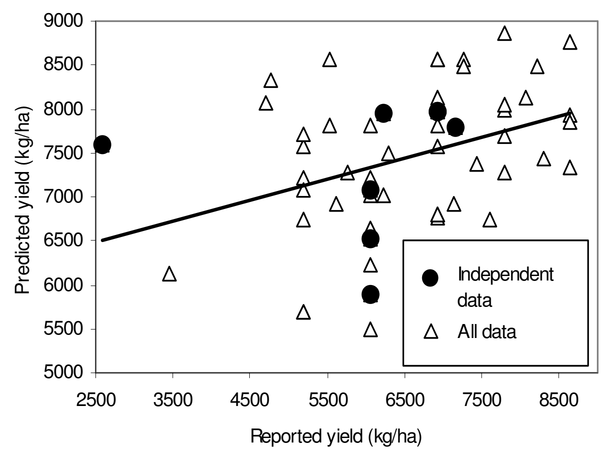


Figure 5.1 Scatter plot for predicted yield versus reported yield fitted with regression line.

Table 5.4 Test results of the integrated model.

	Reported Yield (Y_r) (kg/ha)	Predicted Yield (Y_p)(kg/ha)	Difference (Y_r - Y_p) (kg/ha)	% Difference $((Y_r - Y_p)/Y_r)*100$
1	6054	6288	552	9.1
2	6919	7971	-1052	15.2
3	6054	6529	- 475	7.8
4	2595	7589	- 4994	192.4
5	6054	5825	159	2.6
6	7150	7795	-645	-9.0
7	6227	7950	1723	27.7
8	6054	7085	-1031	17.0
Mean	5888	7138	-257	32.2

5.3 Yield prediction with other VIs

Other vegetation indices were calculated to test if they can have a better prediction ability than NDVI. These VIs include Soil Adjusted Vegetation Index (SAVI), Modified Soil Adjusted Vegetation Index (MSAVI2), Infra-red Percentage Vegetation Index (IPVI), Difference Vegetation Index (DVI) and the Ratio Vegetation Index (RVI) (see appendix 4 for details). Test for correlation between the VIs was significant ($p = 0.00$).

Table 5.5 shows the R^2_{adj} for the fitted logarithimic regression line for the different VIs versus yield. It shows that RVI explains slightly more of the yield variability than any of the VIs and DVI explains the least.

Table 5.5 Prediction ability of different VIs

	NDVI	SAVI	MSAVI	IPVI	DVI	RVI
R^2_{adj}	25.0	26.2	25.9	26.8	22.7	26.9

Testing yield predicted using these VI based models resulted in very little improvement in the yield prediction ability at field level. Table 5.6 shows the R^2_{adj} for different VI based models. It shows that IPVI based model explains slightly more than the other VI based models. With the exceptional of DVI based model, the difference is less than 1% in all cases).

Table 5.6 R^2_{adj} for different VI based models.

	NDVI	SAVI	MSAVI	IPVI	DVI	RVI
R^2_{adj}(%)	45.7	46.0	45.9	46.4	43.7	46.3

From these results, the use of NDVI, which is the most commonly used VI, remains valid.

6 Discussion and Recommendations

6.1 Discussion

Through integration of remotely sensed data, land factors and management aspects, an assessment of field level yield prediction has been executed. It is shown that a combination of NDVI, land and management parameters can improve field level yield prediction above use of NDVI alone. It is found that the availability of water, the weeding method, the number of fertiliser applications, soil type and the date of transplanting explain yield variability. The date of transplanting and the soil type are found to relate to the NDVI variability at field level.

6.1.1 NDVI as yield prediction parameter

This study established that there is a significant positive relationship between remotely sensed Normalised Difference Vegetation Index and field level yield ($r = 0.520$, $p < 0.05$), where production is at the mercy of many factors acting on the crop. This clearly shows the potential of using NDVI for yield prediction at field level.

Among all the NDVI parameters, only maximum NDVI was retained as significant variable for field level yield prediction in the stepwise multiple regression, explaining 25.0% of the yield variability suggesting that maximum NDVI is the best parameter for yield prediction. Groten and Ilboudo (1996) also found similar results where only the maximum NDVI was retained after running multiple regression with many NDVI parameters in millet yield estimation. However, the prediction ability is low, suggesting that if only NDVIs are used for field level yield prediction, a lot of additinal factors explaining yield variability are not covered. NDVI explains the yield variability caused by date of transplanting and soil. It does not reflect other production factors like availability of water and other management factors.

Water shortage had a significant impact on yield but not on NDVI. This suggest that the problem was not severe enough to be registerd by NDVI. This gives the impression that temporal water shortage is, in the first instance, not reflected by lower vegetation cover. However, water shortage at critical stages, stages 6 and 7 (see section 2.3) have a greater effect on yield than on NDVI, even if it occurred during a short period of time, which this may have been the case.

The use of land and management parameters alone has shown that 38.1% of the yield variability can be explained. The combination of NDVI, land and management factors together improved the model to an explanatory power of 45.8%. This shows that use of NDVI alone, as done in many studies, can be improved if land and management factors are also considered, especially at field level where parameters vary from field to field, as opposed to regional or national level, where these factors are generalised.

Despite the fact that this study used interview data of the previous season, relying on farmers ability to remember exactly when an operation was done and how or how much fertilisers and other management practices were done, the results agree with studies done before. Muthy *et al.* (1994) reported correlations (r = 0.44 – 0.85) between NDVIs and yield in irrigated rice in command areas under Bhadra project and reported a yield prediction model that explained 75% of the yield variability. Mohd *et al.* (1994) found correlation of 0.85 between NDVI and yield when he conducted a study based on 2 x 2 m area and collected spectral data with a hand held radiometer.

All these findings indicate that there is correlation between remotely sensed spectral data and yield. The differences in the correlations and explaining ability of yield variability is due to the level of application and the quality of data being used to investigate the relationships and to derive models. Muthy *et al.* (1994) used yield estimates from CCE, which are fairly accurate and used time composited NDVI. Mohd *et al.* (1994) used yield from highly controlled research plots. This study used data collected through interviews. From the results of this study, it is evident that the quality of data may have a significant effect on the degree of the relationships between remotely sensed NDVI and yield.

The results of this study also agree with studies done with other crops. Rajak *et al.* (2002) found that maximum NDVI was linearly related to yield for various crops in Punjab and Haryana states and grown during Rabi 2000 – 2001. They reported that the yield was poorly correlated to NDVI. Ray *et al.* (2002) reported correlations of 0.60 between NDVI and wheat yield in Jajandhsr – Punjab. Gat *et al.* (2000) reported an NDVI yield prediction model explaining 26.6% (R^2) of the yield variability in beet under research.

6.1.2 Model performance

This study has also shown that the use of other vegetation indices to predict yield or using models based on other VIs, did not offer any significant improvement in explaining the yield variability. Even linear transformations and combinations of NDVIs and other vegetation indices in different forms did not improve the model's prediction ability. This suggest that use of NDVI for crop development and growth monitoring and for yield estimation is valid as reported by many authors. Gat *et al.* (2000) also noted the correlations between VIs and linear transformed VIs could not perform any better than the original VIs and he proposed to use the original VIs without any transformation.

Testing the model with independent samples drawn randomly from the data, has shown that the predicted yield fall within the other yields when all the samples are used. With a regression line explaining 12.4% of the variability.

6.1.3 Using single date image for yield prediction.

This study has demostrated that, with a single date image, field level yield can be predicted up to 45.8%. This agrees with the range of 6% - 83% as reported by Parihar and Dadhwal (2002) and

Dadhwall and Ray (2000) of explained yield variability when single date image based models for various crops including rice are used in some states of India. However, the reported variability by the two authors was at state level with a lot of generalisations and using district level yield estimates. The results of this study shows that, even at field level, despite the great variability in planting date, and other factors, single date images can provide useful information of the crops and yield status.

The timing of the image to be used for yield estimation is important. Though Gielen *et al.* (2001) explained that there is good correlation between NDVI and yield but using NDVI as an end-of-season yield estimator gives unsatisfactory results because of the problems of choosing the best time of the image to use, Muthy *et al.* (1994) found that vegetation indices calculated from images taken at panicle initiation and heading stages have high correlation with yield, therefore, they can best be used for yield prediction. The findings of Muthy *et al.* (1994) agrees with the findings of this study.

However, it is difficult to have a single date image representing one phenological stage at field level because of the differences in planting dates and the varieties used, resulting in wide differences in crop phenological stages. To improve the predictability of yield, Muthy *et al.* (1994) and Gat *et al.* (2000) proposed the use of time composited multi-date images for yield prediction covering panicle initiation and heading stages and considering maximum NDVI which normally occurs at heading stage in rice. It is difficult, especially in most tropical environments, to get a series of images due to clouds or other logistical problems. In this case a single date image, as demonstrated in this study, still provides good information to predict end-of-season yield as long as it is within the time when there is maximum vegetation (between panicle initiation and heading stage) and other production factors are taken into account.

It should be noted that plant ultimate growth is affected by its growth history and all the environmental parameters, therefore, remote sensed data and other data are required to develop a functional relationship between plant condition and yield at field level. The use of data acquired from space-borne sensors will help to reduce the need for the laborious ground based measurements and enhance the timeliness of information on crop condition and food situation. However, it should be realised that the predicted yield at any stage of plant growth account for all the factors that affect the crop from planting date to the time of prediction. This is then projected to the final yield. As such predicted yield reflects potential yield of the crop with the prevailing conditions. Factors such as drought, floods, pests and deseases happening after the prediction may significantly reduce the yields.

6.2 Recommendations

This study has develop a yield prediction model for field level. The data used in this study was provided by farmers through interviews. As such there might be a lot of anomalies in the reported data that has to be verified before final conlusions are drawn on its accuracy and applicability. There is need for further research to find more factors that can explain yield variability at field level and improve the model. Based on this the following recommendations are drawn:

1. There is need for further investigation on the factors that contribute to yield variability at field level. Factors such as soil type used in this study were at higher level and more generalised, developed from 1:50,000 maps. As such, it could not provide detailed variation that may occur at field level. There is need for detailed study on the soil characteristics at field level and include factors like pH, texture for specific areas / fields which have a significant effect on water holding capacity, nutrient availability and on yield.
2. This study observed that there is no relationship between N: P: K and yield and N:P:K and NDVI. However, all the farmers applied fertiliser at different times, different rates and types. Therefore, it is proposed that an in depth study on fertiliser use efficiency is required to establish fertiliser utilisation, losses and the gaps existing at field level.
3. The water being used for irrigation is mainly ground water, which is pumped into the paddy fields. There is need to assess the quality of water, ground water recharge and specific ground water depth for the area, which may have impact on water availability and yield.
4. In the analysis, it has been shown that other vegetation indices (including those that takes into account soil influences) have not performed better than the NDVI. Nevertheless, these have been claimed to perform much better than VIs that do not take into account soil influences on reflectance. In view of this it is suggested that there is need to find and establish specific soil reflectance in the area and apply the actual soil reflectance when dealing with Soil adjusted VIs rather than using the generally applied factor of 0.5 for all the soils and at any vegetation density.
5. The study did not consider the previous land management practices, which may have a residual effect on crop growth and production. Zinc is normally applied at two-year intervals and this has not been considered if some farmers applied Zinc in the previous season prior to the season in question. However, it is important to assess this and incorporate into the model if found to be significant.

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Appendices

Appendix 1 Checklist for field data collection

DATE:………………………………. Sample No:………………………..
Name of farmer………………………………………………………………………

1. GENERAL INFORMATION:

field size:
From farmer: ……………………………………..
GPS measurement:……………………………….
Ownership:……………………………………………………..
Soil Type (Local Name):………………………………………………

2. Crop calendar:
How many crops did you grow last year? When?

3. Ploughing:
When did you start land preparation? How? Source of power? Number of ploughings / puddlings?

4. Planting:

When did planting start? How? Seed rate for nursery? Plant used %? Variety? Plant quality? (Good/ average/ poor) Age at transplanting? Source of seed? Water availability? (Water level/ shortage).

5. Fertiliser application:
Number of fertilizer applications? When? How? Type? Quantity? Water level? (before and after).
How long does the water drain after supplying?

6. Weeding:
When? How?

7. Pesticide application:
When? Why? Severity of damage? Names of pest/ disease?
Control method? How?

8. Yield:

When was it done? How much did they harvest? How much did they expect?
Why the difference? Problems - water shortage
Input availability
Extension

How much was the reduction?

9. Farmer suggestions.

What are your plans to increase yield? Which type of support do you expect?
Would you like to change the crop? Why? To which crop / variety?

Appendix 2 Standardised Codebook for field data entry

CHECK LIST DATA	PARAMETER CODE	NAME OF PARAMETER	PARAMETER UNIT	PARAMETER VALUE / OPTION	PARAMETER VALUE NAME	REMARKS
Sample No	S/N	Sample Number				
Sample ID	SAMPLE_ID	Sample Identity				
Field size	AREA_SQM	Area in square metres	m^2			area from the polygons after processing.
Mandal Name	MNAME	Name of the Mandal				
Village Name	VNAME	Name of the village				
Variety	VAR	Variety grown in Rabi		MTU	MTU 1010	
				BPT	BPT 5204	
				M7	M7	
				Era	Eramalelu	
				IR	IR64	
				JGL	Jegthyal (JGL 1798)	
				TH	Thella Hamsa	
Soil	ST	Soil Type	A1			Reclassified soil into new sub-groups based on USDA classification
			B2			
			C2			
			E			
			E			
	DRN	Rate of water loss (drainage rate)	Millimeter per day	mm/d		Estimated by the farmer
Ploughing	P1J	Day of 1st ploughing, day of the year	Days			Days from January 1 2002
	PM1	1st Ploughing method		T	Tractor	
				A	Animal	
	P2J	Day of 2nd ploughing, day of the year	Days			Days from January 1 2002
	PM2	2nd Ploughing method		T	Tractor	
				A	Animal	
	P3J	Day of 3rd ploughing, day of the year	Days			Days from January 1 2002
	PM3	3rd Ploughing method	Days	T	Tractor	
				A	Animal	
Puddling	PU1J	1st Puddling, day of the year	Days			Days from January 1 2002
	PUM1	1st puddling method		T	Tractor	
				A	Animal	
	PU2J	2nd Puddling, day of the year	Days			Days from January 1 2002
	PUM2	2nd puddling method		T	Tractor	
				A	Animal	
	PU3	3rd Puddling	Days			Days from January 1 2002
	PUM3	3rd puddling method		T	Tractor	
				A	Animal	
Planting	DOSJ	Sowing date, day of the year	Days			days from Jan. 1, 2002
	SR	Amount of seed sown	kg/ha			seed rate was reported in number of bag sown and was converted to kg/ha
	DoTJ	Date of transplanting, day of the year	Days			Days from January 1 2002
Basal dressing	DAPB	Diammonium Phosphate fertiliser	kg/ha			All the fertiliser rates were reported in kg/acre or number of 50 kg bags used and were converted to k/ha
	UB	Urea basal dressing	kg/ha			
	C1B	20:20:0 basal dressing	kg/ha			
	C2B	17:17:17 basal dressing	kg/ha			
	C3B	19:19:19 basal dressing	kg/ha			
	C4B	12:32:18 basal dressing	kg/ha			
	SSPB	Single Supper Phosphate	kg/ha			
	KB	Muriate of potash basal dressing	kg/ha			
	ZNB	Zinc basal dressing	kg/ha			
1st top dressing	DoF1J	date of 1st fertiliser application	Days			days from Jan. 1, 2002
	U1	Urea 1st application	kg/ha			All the fertiliser rates were reported in kg/acre aor number of 50 kg bags used and were converted to k/ha
	DAP1	Diammonium Phosphate fertiliser	kg/ha			
	C11	20:20:0 1st application	kg/ha			
	C21	17:17:17 fertiliser 1st application	kg/ha			
	C31	19:19:19 1st application	kg/ha			
	C41	12:32:16 1st application	kg/ha			
	C51	14:28:28 1st application	kg/ha			
	SSP1	Single Supper Phosphate	kg/ha			
	K1	Muriate of potash 1st application	kg/ha			
	ZN1	Zinc or other micronutrients	kg/ha			

Appendix 2. Standardised Codebook for field data entry Continue

CHECK LIST DATA	PARAMETER CODE	NAME OF PARAMETER	PARAMETER UNIT	PARAMETER VALUE / OPTION	PARAMETER VALUE NAME	REMARKS
Second top dressing	DOF2J	Date of 2nd top dressing	days			days from Jan. 1, 2002
	U2	Urea 2nd application	kg/ha			
	C12	20:20:0 2nd application	kg/ha			
	C22	17:17:17 2nd application	kg/ha			
	C32	19:19:19 2nd application	kg/ha			
	K2	Muriate of potash 2nd applications	kg/ha			
	ZN2	Zinc or other micronutrients	kg/ha			
third top dressing	DOF3J	Date of t3rd application	Days			days from Jan. 1, 2002
	U3	Urea 3rd application	kg/ha			All the fertiliser rate were reported in kg/acre or number of 50 kg bags and were converted to k/ha
	U3	Urea 3rd application	kg/ha			
	S_A	Ammonium sulphate 3rd application	kg/ha			
	C13	20:20:0 3rd application	kg/ha			
	C23	17:17:17 3rd application	kg/ha			
	C33	19:19:19 3rd application	kg/ha			
	SSP3	Single Supper Phosphate	kg/ha			
	K3	Muriate of potash 3rd application	kg/ha			
Irrigation	DOIFM	depth of water during fertiliser application	millimeter	mm		The units were reported in Inches and were converted to mm
	DOIM	Normal depth if water in fields	millimeter	mm		
	W1J	date of first weeding, Day of the year	day			days from Jan. 1, 2002
	WM1	method of 1st weeding		H	Hand weeding	
				C	Weedcides	
	W2J	date of 2nd weeding, day of the year	day			days from Jan. 1, 2002
	WM2	Method of second weeding		H	Hand weeding	
				C	Weedcides	
Pest management	PST	Type of pest		SB	Stem borer	
				BPH	Brown plant hopper	
				LF	Leaf folders (caterpillars)	
				RD	Rodent/Rats	
				NP	No pest	
	CM	Control method		PC	Pesticide application	
				NC	No control	
	DPS1J	chemical application, day of the year	day			
	DPS2J	chemical application, day of the year	day			
	MDP	Method of pesticide application		B	Broadcasting	
				S	Spraying	
	INSD	Damage due to insect		n	No damage	Farmers perception
				m	Minor damage	
Disease control	TD	Type of disease		BL	Blast	
				ND	No Diseases	
	DCM	Disease Control method		C	Use of chemicals	Farmers perception
				n	No control	
	DISD	Degree of damage due to diseases		n	No damage	
				m	Minor damage	
Water availability	WS	Period of water shortage		WS_NS	No water problem	
				WS_GR	Grain filling /Flowering stage	
				WS_IRR	Irregular water supply	
	DOHJ	Harvesting date day of the year	day			days from Jan. 1, 2002
Vegetation indices	NDVI	Normalised Vegetation Index		max	NDVI aggregated by maximum	Calculated from IRS image
				mean	NDVI aggregated by mean	
				median	NDVI aggregated by median	
	SAVI	Soil Adjusted Vegetation Index		max	SAVI aggregated by maximum	
				mean	SAVI aggregated by mean	
				median	SAVI aggregated by median	
	MSAVI	Modified soil adjusted vegetation index		max	MSAVI aggregated by maximum	
				mean	MSAVI aggregated by mean	
				median	MSAVI aggregated by median	
	IPVI	Normalised Vegetation Index		max	IPVI aggregated by maximum	
				mean	IPVI aggregated by mean	
				median	IPVI aggregated by median	
	DVI	Normalised Vegetation Index		max	DVI aggregated by maximum	
				mean	DVI aggregated by mean	
				median	DVI aggregated by median	
	RVI	Normalised Vegetation Index		max	RVI aggregated by maximum	
				mean	RVI aggregated by mean	
				median	RVI aggregated by median	

Appendix 3 Data used for the study

3.1 Field data

S/N	SAMPLE ID	AREA_SQM	MNAME	VNAME	VAR	SOIL_TP	DRN	P1J	PM1	P2J	PM2	P3J	PM3	PU1J	PUM1
1	d1s1	16240.2	Kortigiri	Ethoda	MTU	C2		-5	A	4	A	0	0	35	T
2	d1s2	7635.0	Kortigiri	Chikapalle	M7	C2		10	T	0	0	0	0	9	T
3	d2s1	15800.2	Kortigiri	Kodichella	MTU	C2	11	2	T	4	T	3	T	23	T
4	d2s3	12918.4	Kortigiri	Karegoan	MTU	B2	5	-27	T	-24	T	0	0	-21	T
5	d2s4	14428.2	Kortigiri	Karegoan	MTU	B2		-27	T	-20	T	0	0	16	T
6	d3s2	22324.9	Kortigiri	Rampur	Era	D		-57	T	-20	T	0	0	-5	T
7	d4s1	28094.7	Birkur	Barangedgidabha	MTU	C2	3	-35	T	-27	T	0	0	-5	T
8	d4s2	15078.4	Birkur	Barangedgidabha	MTU	C2	7	-27	T	-6	T	0	0	3	T
9	d4s4	8247.8	Birkur	Timampur	MTU	C2	7	-27	T	-5	T	0	0	4	T
10	d4s5	14061.0	Birkur	Timampur	MTU	B2	10	-27	T	-5	T	0	0	4	T
11	d4s6	16068.6	Birkur	Timampur	MTU	B2	6	-27	T	-20	T	0	0	-5	T
12	d4s8	20624.5	Birkur	Nasrullabad	BPT	D	3	-27	T	-22	T	0	0	-5	T
13	d5s1	34666.5	Kortigiri	Sunkini	MTU	A1	15	-16	T	-6	T	0	0	4	T
14	d5s2	6693.9	Kortigiri	Kolur	MTU	C2	38	-20	T	0	0	0	0	-5	T
15	d6s1	38990.1	Birkur	Burkur	MTU	E	25	-27	T	0	0	0	0	2	T
16	d6s3	45887.6	Birkur	Birkur	MTU	E		-27	T	-5	T	0	0	1	T
17	d6s2	20543.5	Birkur	Birkur	BPT	E	19	-27	T	-20	T	0	0	4	T
18	s6s5	27639.3	Birkur	Baswapali	MTU	C2	9	-20	T	-5	T	0	0	9	T
19	d7s3	8919.7	Kortigiri	Raikur	MTU	C2		-20	T	-5	T	0	0	4	T
20	d7s4	7717.2	Kortigiri	Raikur	MTU	A1	9	-27	T	-13	T	0	0	4	T
21	d7s5	22524.4	Kortigiri	Diddhapur	MTU	C2		-27	T	-20	T	0	0	4	T
22	d7s6	7669.9	Kortigiri	Diddhapur	MTU	C2	51	-27	T	-20	T	0	0	4	T
23	d7s7	8475.6	Kortigiri	Diddhapur	MTU	A1		-16	T	0	T	0	0	4	T
24	d8s1	14205.4	Kortigiri	Jellapali	MTU	D	76	-35	T	-20	T	0	0	1	T
25	d8s2	7677.7	Kortigiri	Jellapali	Era	C2		-27	T	-26	T	0	0	17	T
26	d8s3	20533.8	Kortigiri	Jellapali	Era	C2		-27	T	-26	T	0	0	17	T
27	d8s4	3928.5	Kortigiri	Jellapali	M7	D		-13	A	4	A	0	0	9	A
28	d8s5	3689.6	Kortigiri	Jellapali	MTU	D		-35	A	-27	A	0	0	-6	A
29	d8s6	22562.8	Kortigiri	Jellapali	BPT	C2		-27	T	-22	T	-21	T	4	T
30	d9s2	19433.7	Birkur	Myalaram	BPT	C2	76	-29	T	-25	T	0	0	-8	T
31	d10s2	18287.0	Birkur	Damalancha	MTU	B2		2	T	6	T	0	0	8	T
32	d10s4	20896.5	Birkur	Ankole	MTU	C2		-27	T	-27	T	0	0	352	T
33	d11s4	18183.6	Kortigiri	Kallur	MTU	E	25	-27	T	-24	T	0	0	4	T
34	d11s6	37674.0	Kortigiri	Bardhipur	TH	C2	13	-35	T	-20	T	0	0	13	T
35	d12s1	37883.5	Birkur	Nachipalli	MTU	C2	25	-27	T	-16	T	0	0	4	T
36	d12s2	16446.5	Birkur	Nachipalli	MTU	C2	13	-51	T	8	T	0	0	9	T
37	d12s3	7804.0	Birkur	Bommandevpalli	IR	C2	17	-5	T	-5	T	0	0	4	T
38	d12s4	11041.0	Birkur	Bommandevpalli	JGL	C2	7	4	T	4	T	0	0	9	T
39	d13s1	23178.2	Kortigiri	Kothapalli	TH	C2	25	-20	T	-12	T	0	0	-5	T
40	d13s2	8780.7	Kortigiri	Kothapalli	TH	A1		-27	T	4	T	0	0	4	T
41	d13s3	19166.3	Kortigiri	Kothapalli	TH	C2	25	-27	T	-24	T	0	0	349	T
42	d13s4	8011.2	Kortigiri	Kothapalli	TH	C2	9	-27	T	-24	T	-23	T	1	T
43	d13s5	21136.6	Kortigiri	Eklaspur	TH	B2	17	-35	T	-27	T	-21	T	-13	T
44	d13s6	27100.5	Kortigiri	Kortigiri	MTU	C2		-35	T	-27	T	0	0	-5	T
45	d14s1	10784.5	Birkur	Annarum	MTU	C2	15	-27	T	0	0	0	0	-20	T
46	d14s2	9187.7	Birkur	Annarum	MTU	C2	13	-51	T	0	0	0	0	26	T
47	d14s3	7985.7	Birkur	Annarum	MTU	C2	11	-27	T	0	0	0	0	4	T
48	d14s4	13861.6	Birkur	Annarum	MTU	C2	13	-27	T	0	0	0	0	4	T
49	d11s3	22349.5	Kortigiri	Kallur	MTU	E	76	-57	T	3	T	3	T	5	T
50	d2s2	16656.9	Kortigiri	Kodichella	MTU	C2		-5	T	9	T	0	0	9	T
51	d11s1	21219.2	Kortigiri	Kallur	MTU	E	127	-54	T	-46	T	0	0	1	T
52	d11s2	26422.7	Kortigiri	Kallur	MTU	E	64	-54	T	-46	T	0	0	1	T
53	d12s5	17904.1	Birkur	Timmanager	BPT	C2	25	-27	T	-20	T	0	0	4	T
54	d6s6	54299.8	Birkur	Baswapali	MTU	C2	11	-27	T	-13	T	0	0	-5	T
55	d6s7	17020.8	Birkur	Baswapali	MTU	C2	7	-27	T	-20	T	0	0	-5	T

Field data continue

S/N	SAMPLE ID	PU2J	PUM2	PU3J	PUM3	DOSJ	SR	DOTJ	DOBFJ	DAPB	UB	C1B	C2B	C4B	SSPB	KB	ZNB	DOF1J	U1	DAP1
1	d1s1	0	0	0	0	1	74	36	0	0	0	0	0	0	0	0	0	42	62	0
2	d1s2	0	0	0	0	9	74	43	37	0	62	247	0	0	0	0	0	55	62	0
3	d2s1	0	0	0	0	1	74	28	26	185	0	0	0	0	0	0	0	42	0	0
4	d2s3	0	0	0	0	−26	74	15	15	144	62	0	0	0	0	0	0	34	0	0
5	d2s4	0	0	0	0	−26	76	23	5	124	62	0	0	0	0	0	0	24	0	0
6	d3s2	0	0	0	0	−34	74	−7	−7	154	93	0	0	0	0	0	0	9	108	170
7	d4s1	−3	T	−3	0	−26	74	4	4	247	0	0	0	0	0	0	0	24	124	0
8	d4s2	0	0	0	0	−35	99	4	4	185	62	0	0	0	0	0	49	23	124	0
9	d4s4	0	0	0	0	−26	74	5	5	247	0	0	0	0	0	0	0	24	124	0
10	d4s5	0	0	0	0	−26	74	5	5	0	0	74	0	0	0	0	0	24	124	0
11	d4s6	4	T	4	0	−26	74	5	5	0	0	247	0	0	0	0	0	24	124	0
12	d4s8	4	T	4	0	−26	74	5	5	185	0	0	0	0	0	0	0	13	124	11
13	d5s1	0	0	0	0	−19	74	4	4	148	74	0	0	0	0	0	0	20	185	0
14	d5s2	0	0	0	0	2	99	41	10	93	0	0	0	0	0	0	0	56	31	0
15	d6s1	3	T	3	0	−19	62	4	4	0	62	0	0	0	0	0	0	23	124	0
16	d6s3	2	T	2	0	−19	74	4	1	0	124	0	0	0	371	62	49	23	124	0
17	d6s2	0	0	0	0	−19	62	5	5	0	0	247	0	0	0	0	0	20	124	0
18	s6s5	0	0	0	0	−19	74	10	10	0	0	185	0	0	0	0	0	29	62	0
19	d7s3	0	0	0	0	−26	74	5	5	0	31	124	0	0	0	0	0	20	62	0
20	d7s4	9	T	9	0	−19	111	10	10	185	62	0	0	0	0	62	0	24	62	0
21	d7s5	4	T	4	T	−35	74	5	5	185	62	0	0	0	0	0	0	20	62	0
22	d7s6	4	T	4	T	−34	74	17	17	0	62	185	0	0	0	0	0	31	62	0
23	d7s7	4	T	4	T	−26	37	5	5	0	62	0	0	0	494	0	0	20	62	0
24	d8s1	4	T	4	0	−26	74	5	5	185	62	0	0	0	0	0	0	24	62	0
25	d8s2	18	T	18	0	−19	0	18	0	0	0	0	0	0	0	0	0	22	86	247
26	d8s3	18	T	18	0	−19	0	18	0	0	0	0	0	0	0	0	0	22	86	247
27	d8s4	17	A	17	0	−26	74	18	0	0	0	0	0	0	0	0	0	27	124	124
28	d8s5	2	A	2	0	−26	74	7	7	0	124	0	0	0	247	0	0	27	124	0
29	d8s6	4	T	4	0	−26	74	15	15	0	124	0	0	0	371	124	25	29	62	0
30	d9s2	−7	T	−7	0	−34	49	−6	−6	0	0	309	0	0	0	0	0	0	154	0
31	d10s2	9	T	9	0	−26	0	10	10	0	0	247	0	0	0	0	0	35	124	0
32	d10s4	−13	T	−13	0	−26	74	4	4	0	49	0	0	0	124	74	0	17	124	0
33	d11s4	4	T	4	0	−26	62	5	5	0	0	0	0	247	0	0	0	13	49	0
34	d11s6	0	0	0	0	−32	74	15	15	185	62	0	0	0	0	0	0	29	124	0
35	d12s1	0	0	0	0	−26	49	5	5	0	124	247	0	0	0	0	25	20	124	0
36	d12s2	0	0	0	0	−10	55	10	10	0	124	0	0	0	247	0	49	29	124	124
37	d12s3	4	T	4	0	2	124	5	0	0	0	0	0	0	0	0	0	11	185	247
38	d12s4	9	T	9	0	−4	59	17	0	0	0	0	0	0	0	0	0	21	0	247
39	d13s1	4	T	4	T	−26	74	5	5	0	62	185	0	0	0	0	0	20	62	0
40	d13s2	9	T	9	T	−26	74	10	0	0	0	0	0	0	0	0	0	16	124	0
41	d13s3	−16	T	−16	0	−55	74	−14	0	0	0	0	0	0	0	0	0	21	0	0
42	d13s4	3	T	3	T	−26	74	7	0	0	0	0	0	0	0	0	0	13	247	0
43	d13s5	−5	T	−5	T	−14	59	5	5	0	62	185	0	0	0	0	0	20	62	0
44	d13s6	4	T	4	0	−26	74	5	5	247	0	0	0	0	0	0	0	24	124	0
45	d14s1	0	0	0	0	−34	74	−5	−5	0	0	247	0	0	0	0	0	14	124	0
46	d14s2	0	0	0	0	−15	74	27	27	0	0	247	0	0	0	0	0	10	185	0
47	d14s3	0	0	0	0	−26	124	5	5	0	0	247	0	0	0	0	0	24	124	0
48	d14s4	0	0	0	0	−26	82	9	9	0	0	247	0	0	0	0	0	23	124	0
49	d11s3	6	T	6	0	−26	74	13	13	0	0	0	0	0	0	0	49	20	0	0
50	d2s2	25	T	25	0	−4	74	25	0	0	0	0	0	0	0	0	0	40	0	247
51	d11s1	3	T	3	T	−34	74	9	10	0	0	0	247	0	0	0	0	23	124	62
52	d11s2	3	T	3	T	−34	74	9	10	0	0	0	247	0	0	0	25	23	124	0
53	d12s5	9	T	9	0	−12	74	16	16	0	124	0	0	0	247	0	0	40	124	0
54	d6s6	0	0	0	0	−26	74	−5	−5	247	0	0	0	0	0	0	0	14	124	0
55	d6s7	0	T	0	0	−19	74	8	9	0	0	62	0	0	0	0	0	28	62	0

Field data continue

S/N	SAMPLE ID	C11	C21	C31	C41	C51	SSP1	K1	ZN1	DOF2J	U2	C12	C22	C32	K2	ZN2	DOF3J	U3	S_A	C13	C23	C33	SSP3
1	d1s1	247	0	0	0	0	0	0	0	55	49	0	0	0	0	25	75	0	0	0	62	0	0
2	d1s2	0	0	185	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	d2s1	0	494	0	0	0	0	0	0	62	185	0	0	0	247	0	0	0	0	0	0	0	0
4	d2s3	0	144	0	0	0	0	0	0	54	165	0	0	0	136	0	0	0	0	0	0	0	0
5	d2s4	0	247	0	0	0	0	0	0	51	124	0	0	0	62	0	0	0	0	0	0	0	0
6	d3s2	0	0	0	0	0	0	0	31	24	154	0	0	0	95	0	0	0	0	0	0	0	0
7	d4s1	0	0	0	0	0	0	0	0	43	124	0	0	0	12	0	50	62	0	0	0	0	0
8	d4s2	0	0	0	0	0	0	0	0	43	2	0	0	0	62	0	0	0	0	0	0	0	0
9	d4s4	0	0	0	0	0	0	0	0	51	124	0	0	0	62	0	0	0	0	0	0	0	0
10	d4s5	0	0	0	0	0	0	0	0	44	185	0	0	0	62	0	0	0	0	0	0	0	0
11	d4s6	0	0	0	0	0	0	0	0	44	124	0	0	0	62	0	0	0	0	0	0	0	0
12	d4s8	0	0	0	0	0	0	0	0	14	124	124	0	0	0	0	39	62	0	0	0	0	0
13	d5s1	0	0	0	0	0	0	0	30	39	74	0	119	0	74	0	0	0	0	0	0	0	0
14	d5s2	247	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	d6s1	371	0	0	0	0	0	62	0	43	62	0	0	0	0	0	0	0	0	0	0	0	0
16	d6s3	124	0	0	0	0	0	0	0	43	124	0	0	0	0	0	0	0	0	0	0	0	0
17	d6s2	124	0	0	0	0	0	0	0	34	124	0	0	0	62	0	0	0	0	0	0	0	0
18	s6s5	124	0	0	0	0	0	0	8	49	62	0	0	0	0	0	0	0	0	0	0	0	0
19	d7s3	0	247	0	0	0	0	0	0	34	62	0	0	0	62	0	0	0	0	0	0	0	0
20	d7s4	0	0	0	0	0	0	0	0	54	62	0	0	0	62	0	0	0	0	0	0	0	0
21	d7s5	0	185	0	0	0	0	0	0	34	62	0	124	0	37	0	0	0	0	0	0	0	0
22	d7s6	0	0	185	0	0	0	0	0	51	124	0	0	0	62	0	61	62	0	0	0	0	0
23	d7s7	0	0	0	0	0	0	0	0	35	124	124	0	0	124	0	50	0	0	0	0	0	124
24	d8s1	0	185	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	d8s2	0	0	0	0	0	0	0	0	48	86	185	0	0	0	0	85	62	0	0	0	0	0
26	d8s3	0	0	0	0	0	0	0	0	48	86	185	0	0	0	0	0	62	0	0	0	0	0
27	d8s4	0	0	0	0	0	0	0	0	37	124	0	124	0	0	0	0	0	0	0	0	0	0
28	d8s5	0	0	0	124	0	0	0	0	46	62	0	0	0	124	0	0	0	0	0	0	0	0
29	d8s6	185	0	0	0	0	0	0	0	44	62	0	0	185	0	0	59	0	124	0	0	0	0
30	d9s2	0	154	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	d10s2	124	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	d10s4	99	0	0	0	0	0	0	0	24	99	99	0	0	0	0	0	0	0	0	0	0	0
33	d11s4	0	0	0	0	0	0	0	0	50	62	0	124	0	0	0	70	62	0	0	0	0	0
34	d11s6	0	0	0	124	0	0	0	25	56	124	0	0	0	62	0	0	0	0	0	0	0	0
35	d12s1	0	0	0	0	0	49	0	0	39	37	0	0	0	49	0	0	0	0	0	0	0	0
36	d12s2	0	0	0	0	0	0	0	0	54	124	0	0	0	62	0	0	0	0	0	0	0	0
37	d12s3	0	0	0	0	0	0	0	0	21	124	247	0	0	0	0	0	165	0	0	0	0	0
38	d12s4	0	0	0	0	0	0	0	0	31	0	247	0	0	0	0	0	0	0	0	148	0	0
39	d13s1	185	0	0	0	0	0	0	0	34	62	62	0	0	124	0	0	0	0	0	0	0	0
40	d13s2	124	0	0	0	0	0	0	0	24	124	124	0	0	0	0	54	62	0	62	0	0	0
41	d13s3	247	0	0	0	0	0	0	0	31	62	247	0	0	0	0	38	124	0	0	0	0	0
42	d13s4	185	0	0	0	0	0	0	0	26	124	185	0	0	0	0	46	247	0	0	0	0	0
43	d13s5	185	0	0	0	0	0	0	2	39	2	0	0	0	2	0	0	0	0	0	0	0	0
44	d13s6	0	124	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	d14s1	0	124	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	d14s2	185	0	0	0	0	0	0	25	61	62	0	0	0	0	0	0	0	0	0	0	0	0
47	d14s3	124	0	0	0	0	0	0	0	39	124	0	0	0	124	0	0	0	0	0	0	0	0
48	d14s4	0	0	0	0	0	0	0	0	38	0	0	494	0	247	0	0	0	0	0	0	0	0
49	d11s3	0	0	0	0	247	0	0	0	32	124	124	0	0	0	0	57	62	0	0	0	0	0
50	d2s2	0	0	0	0	0	0	0	0	56	247	0	185	0	0	0	76	165	0	0	0	0	0
51	d11s1	0	0	0	0	0	0	0	0	53	124	0	0	0	0	0	90	62	0	0	0	0	0
52	d11s2	0	0	0	0	0	0	0	0	33	124	0	0	0	0	0	48	62	0	0	0	0	0
53	d12s5	124	0	0	0	0	0	0	0	55	124	0	0	0	124	0	0	0	0	0	0	0	0
54	d6s6	124	0	0	0	0	0	0	0	34	0	0	0	0	25	0	0	0	0	0	0	0	0
55	d6s7	124	0	0	0	0	0	0	0	48	124	0	0	0	62	0	0	0	0	0	0	0	0

Field data continue

S/N	SAMPLE ID	K3	DOIFM	DOIM	W1J	WM1	W2J	WM2	PST	CM	DPS1J	DPS2J	MDP	INSD	TD	DCM	DISD	WAT_SH	DOHJ	YLD	WGHT
1	d1s1	0	51	51	56	H	0	0	BPH	PC	0	0	B	M	ND	n	n	WS_GR	115	6054	9
2	d1s2	0			58	H	0	0	SB	PC	0	0	B	M	ND	n	n	WS_GR	115	5189	3
3	d2s1	0	51	76	43	H	0	0	SB	PC	56	0	S	n	ND	n	n	WS_NS	115	8303	9
4	d2s3	0	76		45	H	0	0	BPH	PC	55	0	S	n	ND	n	n	WS_NS	106	8072	7
5	d2s4	0	102		36	H	56	H	BPH	PC	0	0	S	n	ND	n	n	WS_IRR	106	5189	7
6	d3s2	0	32	76	10	H	25	H	NP	NC	0	0	S	n	ND	n	n	WS_NS	85	8216	8
7	d4s1	62	25	51	24	H	40	H	NP	NC	56	0	S	n	ND	n	n	WS_GR	100	6919	9
8	d4s2	0	25	51	7	c	24	H	SB	PC	28	0	S	M	ND	n	n	WS_IRR	100	7438	8
9	d4s4	0	25	51	25	H	45	H	NP	NC	0	0	S	n	ND	n	n	WS_GR	100	6054	8
10	d4s5	0	25	76	25	H	45	H	SB	PC	14	0	S	n	ND	n	n	WS_GR	100	6054	8
11	d4s6	0	19	51	25	H	45	H	NP	NC	0	0	S	n	ND	n	n	WS_GR	100	6919	7
12	d4s8	62	76	76	15	H	0	0	NP	PC	23	0	B	n	ND	n	n	WS_NS	124	6290	6
13	d5s1	0	64	76	19	H	39	H	NP	PC	36	0	B	n	ND	n	n	WS_NS	115	6919	9
14	d5s2	0	64	76	61	H	0	0	NP	PC	0	0	S	n	ND	n	n	WS_IRR	125	6054	9
15	d6s1	0	51	76	7	c	37	H	NP	NC	0	0	S	n	ND	n	n	WS_NS	100	7784	9
16	d6s3	0	25	51	24	H	0	0	LF	PC	34	0	S	n	ND	n	n	WS_NS	100	7784	9
17	d6s2	0	25	51	8	c	0	0	LF	PC	50	0	S	n	ND	n	n	WS_IRR	100	6919	9
18	s6s5	0	25	51	30	H	0	0	NP	NC	0	0	S	n	ND	n	n	WS_GR	106	5189	9
19	d7s3	0	76	76	20	H	0	0	NP	NC	0	0	S	n	ND	n	n	WS_GR	85	6054	8
20	d7s4	0	51	51	15	c	25	H	NP	NC	0	0	S	n	ND	n	n	WS_NS	93	5535	8
21	d7s5	0	51	51	20	H	0	0	NP	PC	40	0	S	n	ND	C	n	WS_IRR	106	7611	8
22	d7s6	62	25		32	H	52	H	NP	NC	0	0	S	n	ND	n	n	WS_NS	124	6919	8
23	d7s7	124	51		8	c	20	H	NP	NC	0	0	S	n	ND	n	n	WS_NS	128	6919	9
24	d8s1	0	25	76	30	H	0	0	SB	PC	25	0	B	n	ND	n	n	WS_NS	128	7784	9
25	d8s2	124	76		38	H	58	H	NP	NC	0	0	S	n	ND	n	n	WS_NS	135	6227	9
26	d8s3	124			38	H	58	H	NP	NC	0	0	S	n	ND	n	n	WS_NS	135	5189	9
27	d8s4	0			33	H	48	H	R	PC	28	38	B	M	ND	n	n	WS_IRR	135	2595	8
28	d8s5	0	51		27	H	47	H	NP	NC	0	0	S	n	ND	n	n	WS_GR	128	3459	8
29	d8s6	0	64		30	H	45	H	NP	PC	45	0	B	n	ND	n	n	WS_IRR	128	5189	8
30	d9s2	0	25	25	16	H	37	H	NP	PC	18	0	S	n	ND	C	n	WS_NS	135	4757	8
31	d10s2	0	51		36	H	0	H	SB	PC	36	0	B	n	ND	n	n	WS_IRR	115	5622	8
32	d10s4	0	19		16	H	28	H	R	PC	28	0	S	M	ND	n	n	WS_IRR	115	5189	9
33	d11s4	0	51	51	20	H	0	0	NP	PC	50	0	B	n	ND	n	n	WS_NS	93	8649	8
34	d11s6	0	51	51	30	H	0	0	NP	NC	0	0	S	n	ND	n	n	WS_GR	105	6054	8
35	d12s1	0	51	51	25	H	0	0	NP	PC	20	0	S	n	ND	n	n	WS_NS	112	7784	8
36	d12s2	0	38		15	c	35	H	BPH	PC	35	60	S	M	ND	n	n	WS_NS	100	6919	8
37	d12s3	0	38	51	22	H	0	0	NP	NC	0	0	S	n	ND	n	n	WS_NS	93	7150	8
38	d12s4	0	51	51	23	H	38	H	NP	PC	32	0	S	n	ND	n	n	WS_GR	93	7127	8
39	d13s1	0	25		20	H	35	H	NP	PC	20	0	B	n	ND	n	n	WS_NS	100	7265	9
40	d13s2	103	25		25	H	40	H	NP	PC	55	0	B	n	ND	n	n	WS_IRR	93	6054	7
41	d13s3	62	25		1	H	0	0	NP	PC	39	0	B	n	ND	n	n	WS_IRR	106	6919	7
42	d13s4	247	25	25	27	H	47	H	NP	PC	27	0	B	n	ND	n	n	WS_NS	100	6919	7
43	d13s5	0	51	51	20	H	40	H	NP	PC	20	0	B	n	ND	n	n	WS_NS	93	6919	7
44	d13s6	0	44	51	25	H	45	H	NP	NC	0	0	S	n	ND	n	n	WS_NS	93	5535	8
45	d14s1	0	25		15	H	0	0	NP	NC	35	0	B	n	ND	n	n	WS_IRR	116	6054	8
46	d14s2	0	25		42	H	0	0	NP	PC	42	0	B	n	ND	n	n	WS_IRR	93	5189	8
47	d14s3	0	25		25	H	40	H	NP	PC	20	0	B	n	ND	n	n	WS_IRR	93	6227	8
48	d14s4	0	38		24	H	39	H	NP	PC	24	0	B	n	ND	n	n	WS_IRR	93	5766	8
49	d11s3	0	64	76	33	H	0	0	NP	PC	58	0	B	n	ND	n	n	WS_NS	93	8649	8
50	d2s2	103	57	51	35	H	0	0	NP	NC	0	0	S	n	ND	n	n	WS_NS	124	4709	9
51	d11s1	62	38		34	H	0	0	SB	PC	24	0	B	n	ND	n	n	WS_NS	93	7784	8
52	d11s2	62	38		34	H	0	0	NP	NC	0	0	S	n	ND	n	n	WS_NS	93	8649	8
53	d12s5	0	51	76	31	H	61	H	NP	NC	0	0	S	n	ND	n	n	WS_IRR	124	6054	8
54	d6s6	0	25	51	-2	c	15	H	NP	PC	28	0	S	n	ND	n	n	WS_NS	100	8649	8
55	d6s7	0	25	51	29	H	49	H	NP	NC	0	0	S	n	ND	n	n	WS_NS	100	7265	8

3.2 Image data

S/N	Sample ID	NDVI			SAVI			MSAVI		
		max	mean	median	max	mean	median	max	mean	median
1	d1s1	0.48	0.4	0.42	0.725	0.595	0.628	0.652	0.564	0.59
2	d1s2	0.35	0.27	0.275	0.525	0.406	0.411	0.519	0.422	0.43
3	d2s1	0.43	0.3	0.309	0.649	0.453	0.462	0.604	0.453	0.471
4	d2s3	0.53	0.47	0.491	0.794	0.697	0.735	0.693	0.637	0.663
5	d2s4	0.51	0.44	0.473	0.757	0.667	0.707	0.671	0.615	0.643
6	d3s2	0.49	0.34	0.371	0.728	0.505	0.555	0.654	0.488	0.54
7	d4s1	0.4	0.22	0.253	0.6	0.331	0.388	0.572	0.349	0.411
8	d4s2	0.48	0.38	0.401	0.721	0.567	0.6	0.649	0.541	0.572
9	d4s4	0.44	0.41	0.421	0.665	0.615	0.63	0.614	0.581	0.591
10	d4s5	0.43	0.27	0.281	0.646	0.4	0.42	0.603	0.411	0.438
11	d4s6	0.51	0.46	0.47	0.757	0.685	0.702	0.671	0.626	0.638
12	d4s8	0.44	0.36	0.399	0.658	0.546	0.6	0.61	0.533	0.572
13	d5s1	0.42	0.23	0.244	0.62	0.342	0.35	0.585	0.353	0.371
14	d5s2	0.33	0.24	0.249	0.498	0.361	0.372	0.499	0.385	0.397
15	d6s1	0.55	0.47	0.469	0.827	0.698	0.703	0.711	0.636	0.642
16	d6s3	0.51	0.45	0.45	0.762	0.669	0.676	0.674	0.618	0.623
17	d6s2	0.49	0.44	0.44	0.738	0.66	0.667	0.66	0.611	0.61
18	s6s5	0.48	0.4	0.436	0.715	0.607	0.644	0.646	0.573	0.606
19	d7s3	0.41	0.29	0.305	0.618	0.438	0.463	0.584	0.452	0.472
20	d7s4	0.4	0.27	0.292	0.604	0.402	0.436	0.574	0.416	0.45
21	d7s5	0.48	0.37	0.408	0.719	0.556	0.622	0.649	0.53	0.587
22	d7s6	0.5	0.43	0.453	0.743	0.647	0.678	0.663	0.601	0.623
23	d7s7	0.4	0.28	0.279	0.594	0.423	0.418	0.567	0.435	0.435
24	d8s1	0.41	0.33	0.347	0.616	0.492	0.518	0.582	0.489	0.514
25	d8s2	0.3	0.25	0.252	0.442	0.376	0.376	0.455	0.4	0.401
26	d8s3	0.28	0.22	0.232	0.413	0.321	0.347	0.432	0.354	0.381
27	d8s4	0.37	0.23	0.195	0.546	0.339	0.292	0.534	0.362	0.325
28	d8s5	0.33	0.23	0.235	0.498	0.338	0.351	0.499	0.363	0.379
29	d8s6	0.46	0.39	0.423	0.692	0.587	0.633	0.631	0.558	0.594
30	d9s2	0.47	0.38	0.39	0.698	0.567	0.591	0.635	0.547	0.572
31	d10s2	0.42	0.29	0.285	0.622	0.441	0.426	0.587	0.444	0.442
32	d10s4	0.44	0.35	0.357	0.657	0.518	0.524	0.61	0.511	0.518
33	d11s4	0.5	0.34	0.406	0.743	0.511	0.608	0.663	0.502	0.58
34	d11s6	0.47	0.32	0.382	0.697	0.487	0.57	0.635	0.477	0.551
35	d12s1	0.52	0.35	0.38	0.773	0.523	0.575	0.681	0.507	0.556
36	d12s2	0.42	0.19	0.148	0.624	0.295	0.221	0.588	0.304	0.256
37	d12s3	0.48	0.44	0.443	0.726	0.653	0.662	0.653	0.606	0.613
38	d12s4	0.42	0.35	0.36	0.635	0.523	0.538	0.595	0.516	0.528
39	d13s1	0.5	0.38	0.386	0.744	0.575	0.577	0.663	0.553	0.555
40	d13s2	0.46	0.29	0.275	0.686	0.427	0.411	0.628	0.429	0.43
41	d13s3	0.49	0.42	0.438	0.729	0.638	0.662	0.655	0.593	0.611
42	d13s4	0.44	0.39	0.397	0.658	0.585	0.594	0.61	0.56	0.567
43	d13s5	0.5	0.29	0.308	0.748	0.43	0.46	0.666	0.415	0.47
44	d13s6	0.5	0.32	0.416	0.743	0.492	0.632	0.663	0.47	0.595
45	d14s1	0.37	0.17	0.16	0.557	0.253	0.24	0.542	0.269	0.276
46	d14s2	0.35	0.25	0.263	0.524	0.378	0.393	0.518	0.398	0.415
47	d14s3	0.43	0.38	0.389	0.641	0.561	0.581	0.599	0.539	0.551
48	d14s4	0.47	0.42	0.438	0.698	0.62	0.654	0.635	0.584	0.608
49	d11s3	0.42	0.37	0.375	0.636	0.558	0.562	0.595	0.54	0.544
50	d2s2	0.38	0.29	0.311	0.574	0.438	0.465	0.553	0.452	0.475
51	d11s1	0.47	0.42	0.436	0.709	0.624	0.652	0.642	0.584	0.606
52	d11s2	0.49	0.41	0.43	0.729	0.618	0.649	0.655	0.58	0.601
53	d12s5	0.37	0.28	0.301	0.556	0.418	0.454	0.541	0.438	0.469
54	d6s6	0.53	0.38	0.425	0.792	0.567	0.644	0.691	0.534	0.601
55	d6s7	0.49	0.36	0.356	0.739	0.534	0.532	0.66	0.521	0.524

Image data continue

S/N	Sample ID	IPVI			DVI			RVI			SPOT VGT
		max	mean	median	max	mean	median	max	mean	median	
1	d1s1	0.742	0.697	0.709	79	61	63	2.9	2.3	2.4	0.35
2	d1s2	0.676	0.636	0.637	52	41	43	2.1	1.7	1.7	0.36
3	d2s1	0.717	0.652	0.654	69	46	48	2.5	1.9	1.9	0.35
4	d2s3	0.765	0.729	0.738	95	78	83	3.3	2.7	2.8	0.42
5	d2s4	0.753	0.723	0.737	88	73	76	3	2.5	2.6	0.42
6	d3s2	0.744	0.668	0.686	77	49	51	2.9	2	2	0.41
7	d4s1	0.701	0.61	0.627	59	31	37	2.3	1.7	1.7	0.35
8	d4s2	0.741	0.687	0.701	80	58	62	2.9	2.2	2.3	0.39
9	d4s4	0.722	0.705	0.711	72	63	64	2.6	2.3	2.4	0.39
10	d4s5	0.716	0.635	0.641	64	41	43	2.5	1.8	1.8	0.39
11	d4s6	0.753	0.729	0.735	85	74	76	3	2.6	2.7	0.43
12	d4s8	0.72	0.679	0.699	67	53	55	2.6	2.1	2	0.38
13	d5s1	0.707	0.614	0.617	61	32	33	2.4	1.7	1.7	0.24
14	d5s2	0.667	0.621	0.624	49	37	38	2	1.7	1.8	0.3
15	d6s1	0.776	0.733	0.735	94	74	74	3.5	2.7	2.8	0.65
16	d6s3	0.755	0.724	0.726	82	67	67	3.1	2.6	2.7	0.65
17	d6s2	0.747	0.721	0.72	78	68	69	3	2.7	2.7	0.6
18	s6s5	0.739	0.7	0.715	77	61	64	2.8	2.2	2.2	0.37
19	d7s3	0.707	0.645	0.652	62	42	44	2.4	1.9	1.9	0.36
20	d7s4	0.702	0.635	0.646	61	39	35	2.4	1.8	1.8	0.36
21	d7s5	0.741	0.682	0.704	76	53	57	2.9	2.1	2.2	0.4
22	d7s6	0.749	0.716	0.727	83	70	73	3	2.5	2.6	0.4
23	d7s7	0.699	0.641	0.64	58	39	38	2.3	1.8	1.9	0.42
24	d8s1	0.706	0.663	0.669	65	50	52	2.4	1.9	2	0.32
25	d8s2	0.648	0.626	0.626	42	37	37	1.8	1.7	1.7	0.3
26	d8s3	0.638	0.604	0.614	39	30	31	1.8	1.6	1.6	0.31
27	d8s4	0.683	0.614	0.598	53	36	34	2.2	1.7	1.5	0.3
28	d8s5	0.667	0.613	0.617	51	36	38	2	1.6	1.6	0.32
29	d8s6	0.731	0.693	0.709	74	61	64	2.7	2.2	2.2	0.3
30	d9s2	0.733	0.689	0.698	77	57	59	2.8	2.2	2.2	0.36
31	d10s2	0.708	0.648	0.648	67	47	47	2.4	1.9	1.9	0.33
32	d10s4	0.72	0.673	0.679	70	55	56	2.6	2.1	2.1	0.37
33	d11s4	0.749	0.668	0.699	83	53	61	3	2.1	2.2	0.4
34	d11s6	0.733	0.662	0.679	75	48	51	2.7	1.9	1.9	0.38
35	d12s1	0.758	0.672	0.69	92	58	60	3.1	2.2	2.2	0.37
36	d12s2	0.709	0.601	0.627	63	34	42	2.4	1.8	1.9	0.33
37	d12s3	0.743	0.717	0.714	83	73	74	2.9	2.5	2.5	0.32
38	d12s4	0.712	0.674	0.678	65	54	53	2.5	2.1	2.1	0.32
39	d13s1	0.749	0.692	0.69	87	63	62	3	2.3	2.3	0.32
40	d13s2	0.729	0.643	0.638	78	46	44	2.7	1.9	1.9	0.32
41	d13s3	0.744	0.711	0.72	78	66	67	2.9	2.4	2.5	0.42
42	d13s4	0.72	0.694	0.699	69	61	62	2.6	2.3	2.3	0.42
43	d13s5	0.75	0.648	0.684	84	48	56	3	2	1.9	0.36
44	d13s6	0.748	0.661	0.708	79	48	60	3	2	2.1	0.34
45	d14s1	0.686	0.585	0.58	57	29	34	2.2	1.6	1.5	0.37
46	d14s2	0.675	0.626	0.632	55	40	41	2.1	1.8	1.8	0.32
47	d14s3	0.714	0.688	0.694	67	58	58	2.5	2.3	2.3	0.33
48	d14s4	0.733	0.706	0.712	77	65	66	2.8	2.4	2.4	0.33
49	d11s3	0.713	0.687	0.691	69	54	54	2.5	2.2	2.2	0.4
50	d2s2	0.692	0.648	0.656	61	42	42	2.2	1.8	1.8	0.32
51	d11s1	0.737	0.708	0.718	77	60	64	2.8	2.3	2.4	0.36
52	d11s2	0.744	0.705	0.715	78	62	65	2.9	2.4	2.5	0.36
53	d12s5	0.686	0.638	0.65	51	39	41	2.2	1.8	1.8	0.38
54	d6s6	0.765	0.689	0.712	90	54	62	3.3	2.1	2.2	0.37
55	d6s7	0.747	0.681	0.681	82	53	51	3	2.2	2.2	0.37

Appendix 4 Overview of vegetation indices

Many vegetation indices have been developed and they can be put in groups. First are the basic indices, which are simple combinations of red and NIR. The other group are the indices designed to minimise soil influences. The third group are the indices developed to minimise atmospheric noise. The last group is beyond the scope of this study and will not be discussed here under. The description of these vegetation indices is based on Gielen *et al.*(2001) and Qi *et al.* (1994).

4.1 Basic indices

RVI and NDVI

These are ratio based vegetation indices. RVI is the simplest ratio between NIR and red while NDVI is a ratio between the difference of NIR and red to their sum. see section 2.2 for details.

IPVI

It was proposed to increase the calculation speed. The values are between 0 and 1 and eliminates the need of indicating the signs as in NDVI. It is calculated as follows:

Where; IPVI = Infrared Percentage Vegetation Index, NIR = near infrared and red = Red band of

$$IPVI = \frac{NIR}{NIR + red}$$

the electromagnetic spectrum.

DVI

$$DVI = NIR - red$$

The VI is calculated as:

Where: DVI = Difference vegetation Index, NIR = near infrared band, red = red band

4.2 Indices to minimise soil influences

PVI

PVI is quite sensitive to atmospheric variation. The index values are between –1 and +1. PVI is calculated as:

Where: PVI = Perpendicular Vegetation Index, α = angle between the soil line and the near

$$PVI = \sin(\alpha)NIR - \cos(\alpha)red$$

infrared axis.

WDVI

Weighted Difference Vegetation Index is mathematically simpler version of PVI and has unrestricted range. It is also very sensitive to atmospheric variation. WDVI is calculated as:

$$WDVI = NIR - g.red$$

Where: g = the slope of the soil line

SAVI

Soil Adjusted Vegetation Index is a ratio based VI that took ino account soil back ground influences and tends to reduce this influence by assuming that soil spectra follows the same soil line. This index tends to bridge between the ratio based and perpendicular vegetation indices. SAVI is calculated as:

$$SAVI = \frac{NIR - red}{NIR + red + L} * (1 + L)$$

Where: L = correction factor ranging from 0 (very high vegetation density) to 1 (very low vegetation density). The mostly used value is 0.5 for intemediate vegetation densiy.

MSAVI

There are two Modefied Soil Adjusted Vegetation Indices. They are based on SAVI. The second was developed through an iterative process from the first MSAVI which eliminated the need to calculate the soil line These indices are ratio based. The y are calculated as:

$$MSAVI1 = \frac{NIR - red}{NIR + red + A} * (1 + A)$$

Where: A = 1 – (2 x **s** x NDVI x WDVI) and **s** = slope of the line

$$MSAVI2 = \frac{1}{2} * (2 * NIR + 1) - \sqrt{(2 * NIR + 1)^2 - 8 * (NIR - red)}$$

where: NIR = Near infrared band of the electromagnetic spectrum

red = Red band of the electromagnetic spectrum