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122

Trees and Water:
Smallholder Agroforestry on Irrigated Lands in Northern India

Robert J. Zomer, Deborah A. Bossio, Antonio Trabucco, Li Yuanjie,
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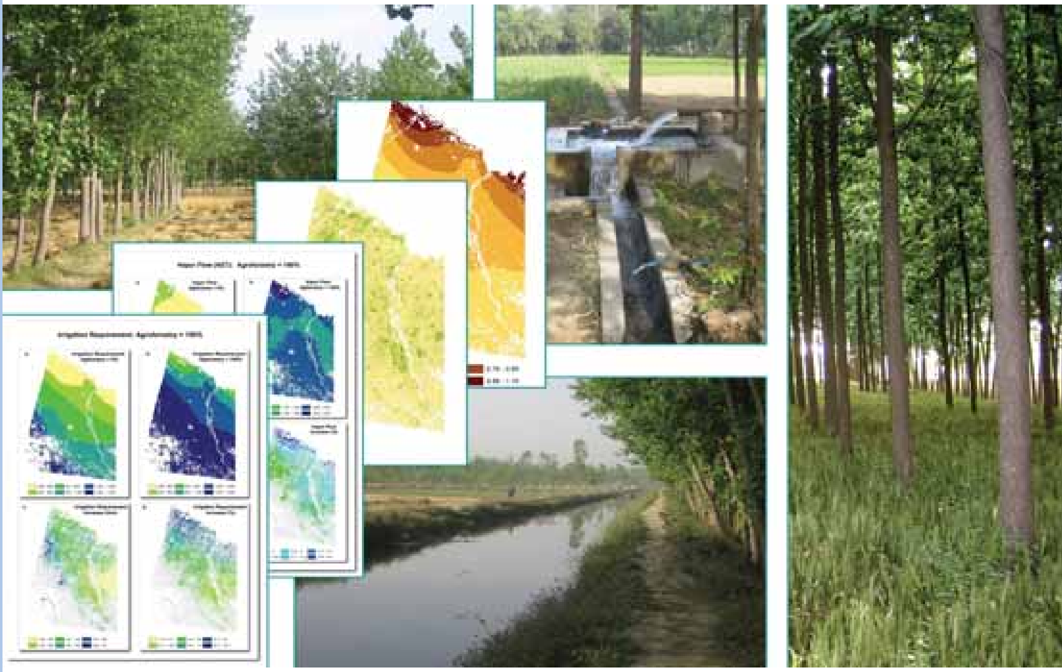

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Trees and Water: Smallholder Agroforestry on Irrigated Lands in Northern India

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Cover picture: Over the last several decades, poplar agroforestry has been adopted by tens of thousands of small farmers, with poplar trees now a common site throughout the irrigated rice-wheat farmlands of northern India (photo credit: Oliver van Straaten).

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Acronyms and Abbreviations

AET	Actual Evapotranspiration
AI	Aridity Index
EC	Electrical Conductivity
ET	Evapotranspiration
ETP	Entire Tree Plant
FAO	Food and Agriculture Organization of the United Nations
FCD	Forest Canopy Density
GIS	Geographic Information System
GPS	Global Positioning System
ICRAF	World Agroforestry Centre
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IWMI	International Water Management Institute
MODIS	Moderate Resolution Imaging Spectrometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
PET	Potential Evapotranspiration
WHO	World Health Organization
WIMCO	Western India Match Company

Summary

Trees are increasingly grown on-farm to supply wood and biomass needs, in both temperate and tropical climates, as well as in developed and developing countries. Over the last several decades, within the irrigated rice-wheat growing lands of northern India, a considerable number of fast-growing poplar trees have been planted on tens of thousands of small farms. This trend is driven by economic incentives (as wood production is often more valuable or less labor intensive) and by national policies (as they aim to limit further deforestation in regional forests). Recent debate regarding tree plantings has raised the issue that water use is often increased when trees are planted. This ongoing debate focuses primarily on afforestation or reforestation of upland and rain-fed agricultural areas, and on resulting off-site impacts such as reduced streamflow. Adoption of poplar agroforestry in northern India, in contrast, is occurring in areas where land and water are already intensively used and managed for agricultural production.

This study used farmer-survey data, remote sensing, and hydrological modeling of the prevalent cropping systems to investigate the importance and role of the poplar trees within the agricultural landscape, and to estimate their water use. It was found that trees are currently grown on approximately 10% of the irrigated lands, which are located within the study area in northern India. The study observed that poplar plantation increased water productivity and profitability of the smallholder farmers. As this agroforestry system replaces an already intensively irrigated cropping system, the establishment of poplar agroforestry on 10% of the area adds only a very marginal increase to the existing water use for crops in this region. The impact on annual irrigation requirement for the region (at the current level of adoption for poplar agroforestry) is estimated to be minimal (1.6% increase), whereas the contribution of poplar trees to the local economy and farmer livelihoods is quite significant and well established. This study concludes that the widespread adoption of poplar agroforestry and other tree-based systems has created a substantial improvement in the water productivity of this intensively irrigated region. In particular, it was found that boundary plantings had little or no impact on regional water use, but could add significantly to 'farmer-livelihood and economic-security'. The importance of growing trees outside of forests, in general, for domestic and industrial uses, and growing trees on-farm, in particular, to directly reduce pressure on forests, wildlife habitat and biodiversity, is highlighted in the study. Overall, these results illustrate a potential for meeting the increasing global demand for wood from trees grown on-farm in irrigated agroforestry systems.

Water and Trees: Smallholder Agroforestry on Irrigated Lands in Northern India

Robert J. Zomer, Deborah A. Bossio, Antonio Trabucco, Li Yuanjie, Diwan C. Gupta and Virendra P. Singh

Introduction

The role of trees within landscapes has been given much attention recently, in contexts ranging from local watersheds to regional impacts and global cycles. As an example, trees, forests and reforestation are specifically identified as viable climate change mitigation measures by the Kyoto Protocol (IPCC 2000), but have also been identified both as carbon sinks and sources. It is evident that widespread and continuing deforestation has significantly reduced the extent of forests globally, in general, and across the tropics, in particular (FAO 2006). Increasing population pressure, and demand for both food and wood have led to the conversion of large areas of forest to agriculture, industrial, urban, and other uses reducing not only terrestrial carbon stocks, but also the supply of easily available wood. The resulting scarcity of fuelwood, timber for construction and wood for a huge array of industrial and commercial uses has imposed significant constraints on the rapidly growing rural societies and the national economies of many developing countries. This is particularly true in the drier and semi-arid regions of the tropics. The rising concern over these issues and the increasing awareness of the important role of trees and forests within terrestrial biogeochemical cycles, have led many countries to impose substantive measures to conserve their remaining forests, further reducing the supply of local wood. Driven both by population growth and increasing standards of living, the demand for wood, as well as the demand for agricultural land, will continue to grow in the future. Producing wood on-farm, either in woodlots or intercropped with other agricultural crops, has been promoted for many years as a partial solution to rising demand. In India, this concept has received widespread support (Puri and Nair 2004); so that a significant proportion of the national wood demand is currently met by what is produced on-farm. Various fast-growing species have been introduced across India specifically to meet the local and regional wood needs. Several of these trees, notably various species of *Eucalytpus* and *Prosopsis*, have given rise to much controversy due to a general impression that their increased water use has a negative impact on water balances (Calder 1992, 2000, 2002).

Across northern India (Figure 1), from Punjab through Haryana and Uttar Pradesh to West Bengal, poplar (*Populus deltoides*) trees, which were introduced in the early 1970s to supply wood to a local match factory, have been widely adopted. These trees are planted on irrigated land traditionally used for cereal production in a rice/wheat rotation. It has been proposed that including a tree component within the farming system, either on bunds and boundaries (sequentially with crops) or intercropped in an agroforestry type configuration, can lead to increased land productivity while diversifying the farming enterprise (Atta-Krah et al. 2004; Huxley 1999; Young 1989), and increase economic security for small farmers (Russell and Franzel 2004). In light of prevailing low grain prices, due in part to successive abundant harvests from these intensively cultivated lands, poplar agroforestry has become increasingly attractive to farmers. In this agroforestry system, poplar and sometimes other trees are planted in

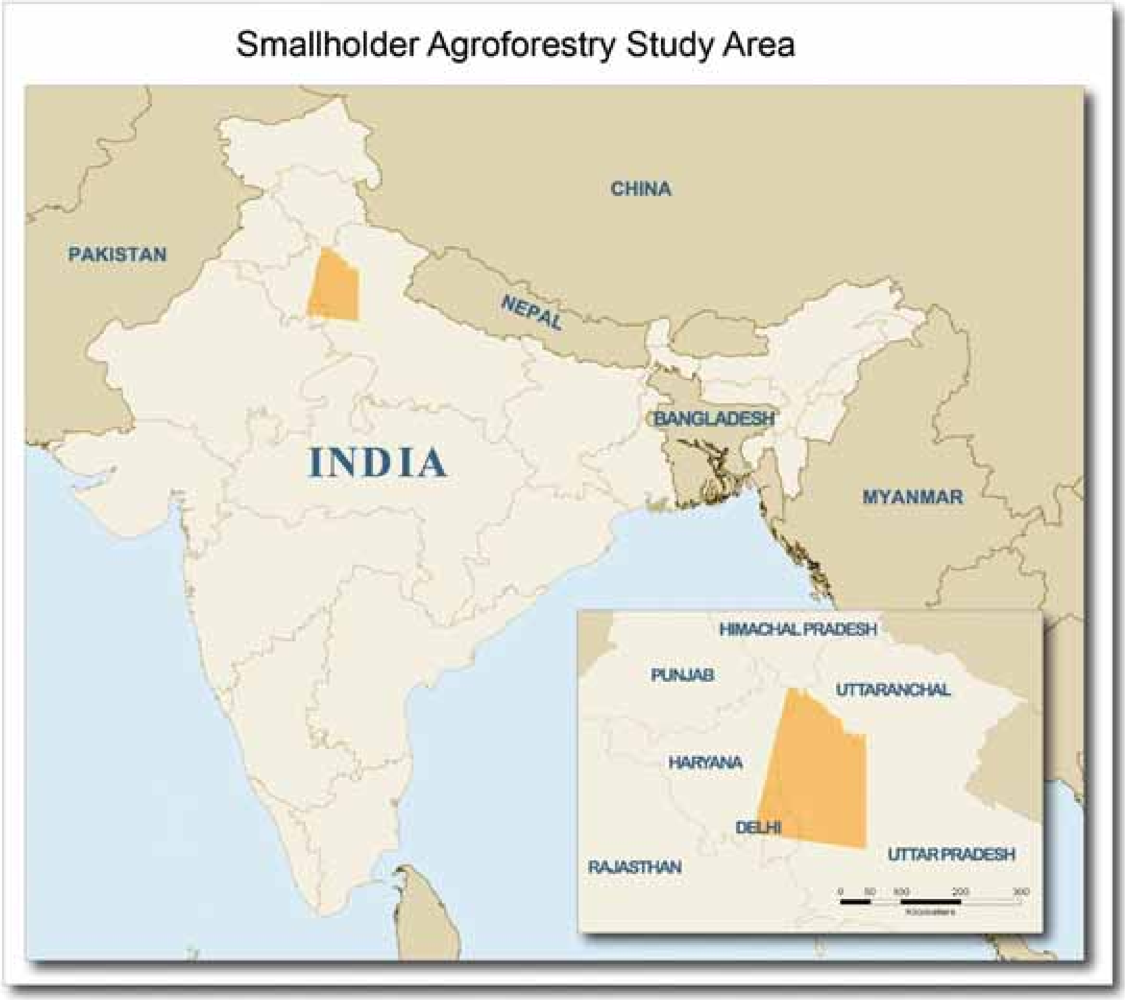

FIGURE 1. Map showing the location of the study area in northern India. Poplar agroforestry stretches in a belt from the Punjab, through Haryana and western Uttar Pradesh states.

association with a variety of crops, including rice, wheat, sugarcane, berseem clover, and sorghum; and, at times, other tree crops such as mango or citrus (Figure 2). These systems provide various products, which contribute to commercial and subsistence agricultural productivity as well as to farm family livelihoods. For example, within the study area, as in many parts of South Asia, cattle manure is commonly burned for fuel (Figure 3). Hopefully, increased regional availability of on-farm woody biomass might allow for a shift to increased use of fuelwood, and the recycling of farm animal manures back into compost and soil to improve farm fertility.

Trees and Water

Numerous projections with regard to water supply and scarcity focus on the rising global population and the increasing need for domestic, industrial, agricultural and recreational water (e.g., IWMI's Global PODIUM online interactive model at http://podium.iwmi.org). Over 1.1 billion people currently lack access to safe and affordable water for their domestic use (WHO 2006). The majority of these people are the rural poor who lack water not only for domestic purposes, but also to sustain their agricultural livelihoods (Rijsberman et al. 2006). To meet growing food demand, water diversion for

FIGURE 2. Poplar is a commonly found intercrop with a variety of complimentary crops, including wheat, sugarcane, berseem clover, various pulses, and other trees like teak and mango. Flood irrigation is commonly used to apply water to both crops and trees.

FIGURE 3. Manure is commonly used as household fuel in many parts of South Asia. On-farm production of fuelwood can have the added benefit of allowing farmers to shift to composting of animal manures, and the recycling of nutrients into the soil. Incorporating farm manure into the soil, while improving fertility and soil structure, can also reduce the need for chemical fertilizers and significantly increase organic matter and soil carbon.

agriculture must rise between 12% and 27% by 2025 (IWMI 2000; FAO 2001, 2003a, 2003b; Shiklomanov 1998). Up to two-thirds of the world's population may be impacted by water scarcity over the next several decades (Shiklomanov 1991; Raskin et al. 1997; Seckler et al. 1998; Alcamo et al. 1997, 2000; Vorosmarty et al. 2000; Wallace 2000; Wallace and Gregory 2002). Maintaining environmental flows to sustain essential ecosystem services is critical, but will be a challenge in the face of these mounting pressures.

Landuse changes such as the adoption of poplar agroforestry can alter the hydrological cycle, affecting both the levels of water use and the total irrigation requirement. Trees, in general, consume more water than other shorter stature vegetation growing under the same environmental conditions, largely as a result of being perennial, and their ability to exploit a larger volume of soil to extract moisture and increased rainfall interception. Jackson et al. (2005), in an analysis of 504 catchment studies scattered across the globe, found that plantations decreased streamflow by an average of 227 millimeters (mm) per year (52%), with 13% of streams drying completely for at least a year. The magnitude of this water flow decrease is proportional to the percentage of vegetation cover, and is due to an increase in actual evapotranspiration *(AET)*, an increase in the net additions to evaporation from interception losses and the larger volume of the root zone under trees, from which water is extracted (Dingman 1993). A review of catchment experiments (Bosch and Hewlett 1982) found that, on average, pine and eucalypt plantations cause a 40 mm decrease in runoff for a 10% increase of forest cover with respect to grassland. The equivalent responses of deciduous hardwood and shrubs are 25 mm and 10 mm decreases in runoff, respectively. Transpiration from trees can be higher than from shorter vegetation because tree root systems exploit deep soil water (Maidment 1992), which is available during the prolonged dry seasons (IPCC 2000).

On-site hydrological effects of afforestation are mainly perceived to be positive (reduced runoff and erosion, improved microclimate, increased control over nutrient fluxes, decreased sediment loads, and increased water quality). However, Jackson et al. (2005) report that afforestation of grasslands and shrublands significantly increased sodium concentrations, exchangeable sodium percentage, and soil acidity, and decreased base saturation, suggesting potential soil salinization and sodicity. In some regions, plantations may have strong negative effects on soil fertility, salinity, and/or groundwater. The off-site effects of afforestation, may be mainly negative (lower baseflow), but in some cases these off-site effects of increased in situ vapor flows may be beneficial for downstream users, for example, as flood control or soil conservation measures, or to prevent leaching or lateral flows of contaminates in groundwater. The debate on forests and water has been the subject of much interest and research (Andréassian 2004; Bruijnzeel 2004; CIFOR and FAO 2005), and is ongoing. More recently, a more nuanced and fact-based school of thought has emerged to make the case for evaluating impacts more site-specifically (based on biogeographical and geophysical criteria), and at appropriate scales. “Seeing the landscape for the forest” is judged to be as important as “seeing the forest for the trees” (van Noordwijk 2006).

Poplar Agroforestry in Northern India

For more than six decades, the poplar (*Populus deltoides*) has been an important tree in northern India, especially in the lowland ‘Terai’ areas at the base of the Himalayas. In 1969, four clones of *P. deltoides* were received from Australia, which propagated rapidly ensuring attractive returns to the leaseholders (Chaturvedi 1982). Subsequently, the Uttar Pradesh (UP) Forest Department experimented with growing wheat, mustard and sugarcane as companion crops in association with the poplar in various configurations. Early adopters, progressive farmers in the Terai region of UP started planting poplar intercrops as early as 1974 (Chandra 2001). Rapid adoption of the poplar, thereafter, coincided with an alarming scarcity in regional wood supplies. Until the late 1970s, almost all of the wood-based industries in India depended on the state forest departments for raw material. That is, most wood came from forests, primarily forests in the Himalayas. A ban on timber cutting in state forests, and the widening gap in demand and supply, meant that wood-based industries had no option but to go to farmers for their raw material needs (Chandra 2003). The Western India Match Company (WIMCO) Ltd., is largely responsible for the introduction and widespread adoption of the poplar agroforestry system. In 1976, WIMCO initiated an extensive publicity campaign promoting the usefulness of poplar plantation in agriculture. They established a Forestry Extension Centre at Rudrapur, UP, to promote cultivation of poplar trees in the region. In 1983, WIMCO distributed 126,000 seedlings free of cost. In 1984, a WIMCO – NABARD (National Bank for Agriculture and Rural Development) poplar project, designed as a joint partnership between the industry and the banking sector, was implemented in selected districts of UP, Punjab and Haryana. The project offered a complete package of services to the tree growers, including:

- improved planting material, grown for the program in the WIMCO nurseries and supplied at the site of planting;
- assistance in obtaining a bank loan for growing trees;
- the package cost for an ETP (Entire Tree Plant) charged by WIMCO included not only the cost of the plant but also follow-up care and cost of the plantation;

- complete guidance for 8 years (till harvest of the trees);
- free replacement of ETP in the initial 2 years (up to 10%); and
- guarantee to purchase the trees at the end of 8 years at an assured price.

During the first phase (1984–1987), almost a million saplings were transplanted in the area. Initially, the Government of UP, accorded permission for poplar agroforestry on 13,600 hectares (ha) of marginal/waste/barren land. However, the program was taken up preferentially by farmers planting on fertile farmland. By 1991, during phase-II of the program, approximately 3.2 million saplings were transplanted in 18 districts of UP. In 1992, the project area was further extended to encompass more districts. In 1994, WIMCO ended its collaborative contractual farming project. The company now provides planting material, technical support and extension to farmers on a cost per tree basis.

Research Objectives

The objective of this study is to understand the hydrologic implications of the increased tree cover within the agricultural landscape of northern India, at farm to regional scales. Most of the studies cited here, and the debate on trees and hydrologic impacts in general, center on afforestation and reforestation of upper catchments. The poplar agroforestry phenomenon, however, is different. Widespread adoption of poplar agroforestry, planting of orchards and other trees are occurring on lowlands that have received significant investment in irrigation infrastructure, specifically to grow food crops. This type of diversification towards perennials and non-staple food crops, within existing irrigation systems is likely to increase in India and elsewhere due to economic pressures. Hence, it is important to understand how this change affects water use. The explosion of interest in biofuels, for example, is likely to radically accelerate this trend.

In this study, a spatially distributed model is used to analyze the water use implications of poplar agroforestry within intensively irrigated and cultivated rice/wheat cropping areas. Estimates of water balance, vapor flow response to land-use change (i.e., adoption of poplar agroforestry), and consequent additional irrigation requirements are reported. A simple water balance approach, combined with the results of a remote sensing analysis of tree cover in the study area, is used to estimate the impacts of poplar agroforestry on hydrological cycles at the farm to regional scale.

The specific objectives of the study

(1) *To Map the Extent of Adoption of the Poplar Agroforestry System and Estimate Tree Cover Within the Agricultural Landscape:* It was necessary to estimate the tree cover in order to model water use at the larger scale. This is not a trivial analysis, because blocks of poplar trees are difficult to discern when young, and many of the poplar plantings are done in narrow long strips along the bunds[1] and canals, which again are difficult to map at larger scales. A multi-phased remote sensing approach first used MODIS data to map the agricultural areas. Forest Canopy Density (FCD) mapping of Landsat ETM+ data was used to derive the tree cover within the agricultural areas. The IKONOS (1-meter [m]) panchromatic imagery was used to assess the accuracy of the tree cover

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[1] The raised banks around the perimeter of irrigation plots in India.

estimates and further calibrate the results obtained from the analysis of the Landsat ETM+ images. Extensive groundtruth data was used to evaluate and validate the results.

(2) *To Estimate the Change in Water Use Resulting from the Inclusion of Trees Into the Agricultural Landscape, Both in Terms of Vapor Flows and Irrigation Requirements:* The challenge is that agroforestry is not a direct substitution of the existing cropping system by trees, while evapotranspiration by the trees varies markedly by season and age. Even within block plantings of poplars, companion crops are grown, with a gradual replacement of the annual crops by a mature agroforestry plantation where the trees dominate evapotranspiration. Therefore, in the study an 'ideal' 10-year cropping system has been defined and modeled to represent the dominant farming systems in the study area. The water use over a period of 10 years of annual cropping is compared to 10 years of agroforestry, i.e., modeled as a combined tree and crop system.

(3) *To Assess the Potential Impacts of Adoption of Poplar Agroforestry on Regional Hydrologic Cycles and Basin Level Water Balance*: In order to upscale the farm-level cropping model to a regional scale, the water use implications of current levels of poplar agroforestry on irrigated lands in northern India were estimated by combining the results from the remote sensing analysis of tree cover with the hydrologic model. This model was applied on a pixel by pixel basis, to provide a disaggregated geospatial analysis of the hydrologic effects.

Methods

This research report is part of a broader study that set out to evaluate the impact, added productivity and other economic and environmental costs and benefits associated with the poplar agroforestry system as found within irrigated agricultural areas of northern India. A field survey was designed and conducted, which included interviews with farmers (using a formal survey), expert informants, and collection of local secondary data and maps. In addition, measurements were taken to estimate the production of biomass and provide groundtruth data for the canopy cover. These results were used to inform both the subsequent remote sensing analysis of land use and tree cover, and the hydrologic analysis of the poplar agroforestry system.

Study Area

Poplar agroforestry is found across a wide belt of northern India, stretching from the State of Punjab across Haryana, through Uttar Pradesh, and further east to West Bengal. This area, between 28 and 30 degrees north latitude, is generally comprised of irrigated agricultural areas of low topography, nominally dedicated to a rice/wheat crop rotation, with substantial area under sugarcane. Farmers, however, may also grow a variety of other crops, such as pulses, vegetables, or forages. Further south in the drier zones of this area, farming systems may be based around sorghum instead. A large number of farmers throughout the area grow poplars on their field, primarily as bund or boundary plantings. Relatively fewer farmers grow poplar in block plantations. These blocks of trees are typically intercropped with other crops, in various agroforestry type configurations. Full sun crops, including rice, sugarcane and wheat are intercropped early in the cycle, with a switch to shade-loving crops like ginger or tumeric as the tree canopy closes. Significant irrigation infrastructure exists in this area, with groundwater contributing most of the total irrigation supply. Agriculture is the main source of livelihood in this area, with poplar-based industries such as plywood manufacture, becoming more important in recent years.

For this study, boundaries of the area of investigation were delineated by the extent of the remote sensing imagery used in the analysis. An area of approximately 32,500 square kilometers within the primary poplar agroforestry belt was identified, for which imagery was available at the required nested scales and seasonally appropriate dates. The average size of landholdings in this area is approximately 2 ha, with few farmers having more than 5 ha. Almost all the soil within the study area is alluvial. Much of this is classified as loam or sandy loam, having a pH range of 6.5–7.5, with some significant areas of sandy soil. Only a small percentage is considered naturally saline, however, waterlogging and irrigation with saline groundwater has exacerbated this issue. The precipitation pattern is monsoonal, with 950 mm of rain falling mostly between the months of June and October. The monthly-average mean temperature is 25°C, with a monthly-average maximum temperature in excess of 40°C, and a monthly-average minimum temperature of 6.5°C. The rainy season starts in June, peaks in July and ends in October.

Field Sampling and Farmer Survey

An extensive field survey was conducted (from October, 2003 to March, 2004) in the Indian state of Uttar Pradesh (UP) to understand the dynamics, extent and rate of adoption of poplar agroforestry. Farmers with block plantations of poplar were interviewed for the survey. A total of 508 'farmer-interviews' and 'field-samplings' were conducted over 53 villages, within five districts of western UP, spanning three agro-climatic zones. A detailed farmer survey based upon individual formal interviews was conducted to provide an overview of poplar production, and to assess its productivity, economic profitability, socioeconomic constraints, and environmental impacts, particularly on the water cycle. Additionally, 500 field plots (25 x 25 m) were sampled to provide biomass production estimates, develop a site index for poplar agroforestry and investigate soil conditions. For each farmer interviewed the following biophysical aspects were measured:

- GPS coordinates of the plot using a handheld GPS
- Measurements of tree diameter at breast height (DBH) of all the trees within a 25 x 25 m sampling plot
- The spacing and the number of trees
- Percentage of canopy cover within the plot
- Salinity (EC) of the water source, e.g., a shallow well, a borehole or a canal, which is the main source of irrigation of the selected plot
- Field observations, which included time of planting, spacing, variety and the companion crops, if any
- Two pooled soil samples, one within the tree area of the sample plot, and another within an associated non-tree area, were collected. These samples were analyzed to determine the soil type, soil quality and fertility status at the ICRISAT Soils Laboratory in Hyderabad, India

Individual farmer-interviews were structured to ascertain production requirements, including agronomic aspects of poplar agroforestry and farming, patterns of investment, and farmer perceptions regarding groundwater levels, water quality and water use. The questionnaire includes details related to planting, agronomic and economic factors, and the management aspects of poplar and the poplar agroforestry system. Detailed discussions were held with each selected poplar grower to ascertain information about livelihood aspects, motivation for adoption of poplar agroforestry, perceptions regarding poplar agroforestry, and specific information about agronomy and intercropping results. An effort was also made to assess the economic returns of poplar agroforestry. In addition to the individual interviews, expert informant interviews were conducted in each district, as well as discussions with poplar traders and plywood manufacturers in the area. A thorough review of secondary sources was conducted as part of the study, including district records of groundwater levels, landuse and salinity maps, socioeconomic statistics, and records from, and interviews with, WIMCO. Full results of this field study are summarized in Gupta et al. (2005), and will be reported elsewhere.

Remote Sensing Analysis of Land and Tree Cover

In order to determine the extent of adoption of this system within the region, and later to examine the impact of poplar agroforestry on water use and vapor flows, a remote sensing analysis of landuse and tree cover was conducted to estimate the area under poplar agroforestry. The analysis was constrained to irrigated areas, typically found dedicated to the intensive rice/wheat cropping systems which are dominant in the study area. Two Landsat ETM+ images (28.5 m resolution) and one MODIS (250 m resolution) image were used for this analysis. The Landsat ETM+ was used mainly to derive tree cover, and MODIS was used to map agriculture areas. A False Color Composition (FCC) of the Landsat ETM+ was used to identify and mask out natural forest cover areas. One IKONOS (1 m) panchromatic image was used to assess the accuracy of the tree cover estimates and to further calibrate the results obtained from the FCD analysis of the two Landsat ETM+ images. High-resolution digital imagery (obtained from Google Earth) was then used to assess the accuracy of the landuse classification and the tree cover estimates (utilizing a stratified random sampling technique within areas where imagery with high spatial resolution was available). Tree cover analysis was limited to the irrigated agricultural area identified from the MODIS data.

Agricultural Area Classification

The MODIS 09 product (NASA) was used to perform a multi-temporal analysis of the land-cover, based on a time series of 107 images taken every 8 days from the year 2002 to 2004. The MODIS 09 product (250 m resolution) is a measure of the land surface reflectance, for each band, at the ground level assuming that there is no absorption or atmospheric scattering (Vermote et al. 2002). Biomass fluctuation over the time-series period was examined by producing a NDVI image for each of the 107 dates. The monthly maximum NDVI (Thenkabail et al. 2005) was used to composite ‘cloud-free’ monthly images. The general result, however, is a smoothing of the NDVI curve over the time-series period. Prolonged periods of cloud cover, for example, as associated with the summer monsoon, may still be problematic.

The NDVI time-series data was classified initially into 60 classes, using a maximum likelihood unsupervised land cover classification (Schriever and Congalton 1995; Zhan et al. 2002). The mean NDVI values of each class were calculated to derive a temporal signature. Agricultural land displayed a relatively regular and recognizable pattern of change over the year. Some irrigated cropping was easily identified by comparatively high NDVI values evident during the dry season. However, in cases where the temporal signature trend is similar to seasonal fluctuation of rainfall, it is more difficult to identify the crop area. An iterative procedure based on comparison with field data (Huete et al. 1997; Hansen et al. 2003) was used to aggregate and then identify 13 classes (Figure 4). The final output map for further analysis has only two classes; agricultural area and nonagricultural area. In general, the agricultural areas within this region (2.9 million ha) were considered to be under some form of irrigation, which was confirmed by fieldwork. This aggregated classification was found to have a relatively high degree of accuracy (> 90%), based on comparison with the groundtruth data.

Estimating Tree Cover

Using remote sensing data for the estimation of the tree cover of “trees outside of forests” (FAO 2006), or in this case, agroforestry, within a highly heterogeneous agricultural landscape of small farmers, is problematic for several reasons. Blocks of poplar trees established as wood plantations become increasingly discernable as they mature and the canopy closes. Young plantations, however, are missed due to low canopy cover. Beyond this, a substantial percentage of poplars in

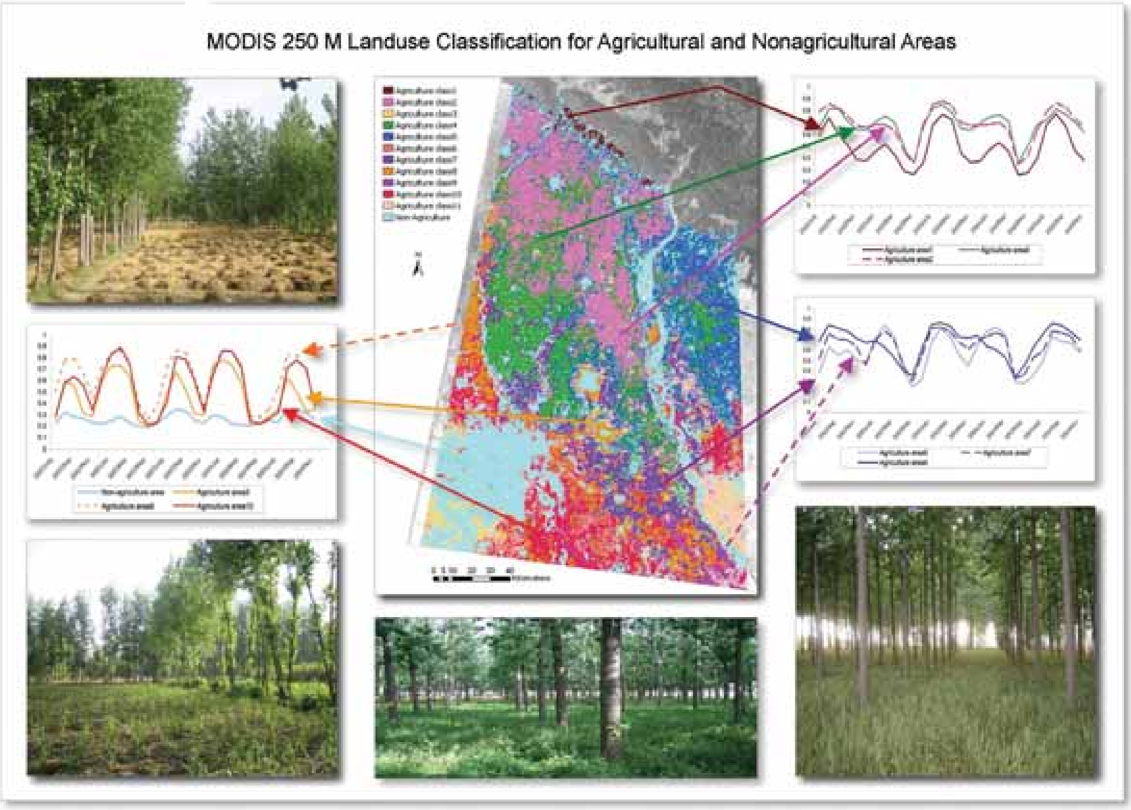
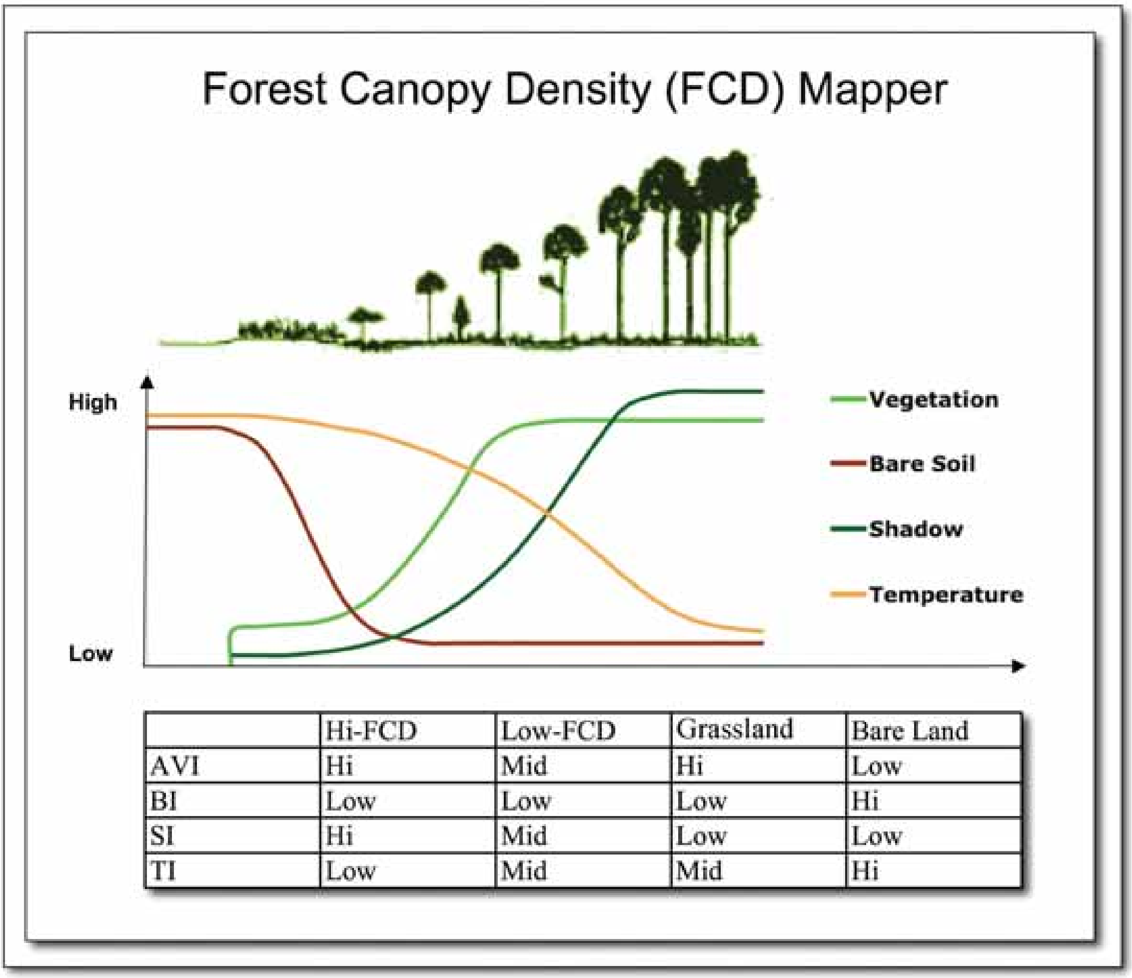


FIGURE 4. Landuse classification based on MODIS 250 meter resolution data, showing agricultural classes and nonagricultural areas. NDVI time series (or temporal signatures) for various classes are shown. Photos illustrate the diversity found in poplar agroforestry and the various intercrops.

the study area are found as bund or boundary plantings, or along roads and canals. These trees are difficult to delineate at available resolutions, e.g., MODIS at 250 m or even Landsat at 25 m. Photo interpretation or multi-spectral classification may require improved spatial resolution in order to discern trees in sub-pixel spatial patterns, or scattered irregularly throughout the landscape. The average width of single line plantings is smaller than one Landsat pixel, but higher resolution data, and its processing, can be prohibitively expensive for assessing larger areas.

To estimate tree cover within the identified irrigated agricultural areas, and to identify poplar (and other) agroforestry systems, the Forest Canopy Density (FCD) Mapping Model and Semi-Expert System (Rikimaru et al. 2002) was used to analyze two sets of adjacent Landsat ETM+ images. The data acquisition date in early May of 2003 corresponds to the harvest time of most of the wheat and sugarcane crops, with poplars approaching full leaf. Images were orthorectified (RMSE=0.45 pixel) using ground control points collected using a handheld GPS. Landsat ETM+ band 6 was re-sampled to 28.5 m resolution by the nearest neighbor method to facilitate the FCD analysis, which uses all seven Landsat TM bands. To estimate the forest canopy cover, the FCD model derives four indices (Figure 5). They are: 1) Advanced Vegetation Index (AVI); 2) Bare Soil Index (BI); 3) Shadow Index (SI); and 4) Thermal Index (TI). The interaction of these four prime indices is characterized along a continuum from treeless landcover to dense forest, and is used to make an estimate of the canopy cover. The output FCD map provides a tree canopy cover percentage for each pixel. An initial desktop analysis was field-tested and subsequently iteratively improved based upon groundtruthing, field-testing, and an analysis of



	Hi-FCD	Low-FCD	Grassland	Bare Land
AVI	Hi	Mid	Hi	Low
BI	Low	Low	Low	Hi
SI	Hi	Mid	Low	Low
TI	Low	Mid	Mid	Hi

FIGURE 5. The characteristics of four prime indices of forest condition as conceptualized within the Forest Canopy Density (FCD) Mapping Model and Semi-Expert System, and used in the remote sensing based estimation of adoption and areal extent of agroforestry within the study area (*Source:* Rikimaru et al. 2002).

the IKONOS (1 m) multi-spectral image as explained further below. A threshold value of 10% canopy cover was used to classify areas of agroforestry, although some of this identified tree cover is either eucalyptus, citrus or mango (all are commonly found in the study area). Since the poplar has a rotation period of 8 to10 years, at any particular time a significant portion of all plantations will have low canopy coverage, especially with the recent increase in new plantations, i.e., plants that are less than 4 years old.

Adaptation of the FDC methodology to quantify agroforestry at the landscape scale was able to provide relatively good results in ascertaining the presence or absence of trees within a pixel. However, it did not provide a good correlation of predicted tree cover with the ground measurements, To overcome this, the detailed manual analysis of the IKONOS imagery described below was used to calibrate the FCD results, and to define the threshold for the agroforestry class, as used in the subsequent hydrological analysis.

Multi-sensor Calibration of FCD Analysis Using High-resolution IKONOS Data

A single multi-spectral IKONOS image (4 m resolution) was used to assess the accuracy of the FCD canopy cover output map within the 7 x 7 kilometer (km) test area. The location of the IKONOS image was chosen to overlap with both of the Landsat ETM + images, facilitating its use in image registration and FCD calibration. Tree cover within this high-resolution image was manually digitized (Figure 6), and groundtruthed during a field visit in April, 2005. The tree shadow can be easily seen on the image, which has a relatively low sun angle, facilitating interpretation. The crown width for boundary plantings was determined to be from 5 to 12 m, with an average width of about 7 m. Digitized tree polygons extracted from the IKONOS imagery were compared with the Landsat derived FCD map (Figure 7). The area of agroforestry within the IKONOS test area was estimated at 487 ha in the FCD analysis of the Landsat images compared to the 444 ha identified in the IKONOS image, representing a difference of about 10%. As the total area of the IKONOS image is 5,140 ha, the tree canopy cover is determined to be approximately 9% of the test area, based on manual digitization. Confusion of tree cover with mature sugarcane, which gives similar reflectance values in the Landsat ETM+ image during early May, is assumed to contribute to the relatively minor overestimation by the FCD analysis in comparison to the manual photo interpretation of the IKONOS imagery.

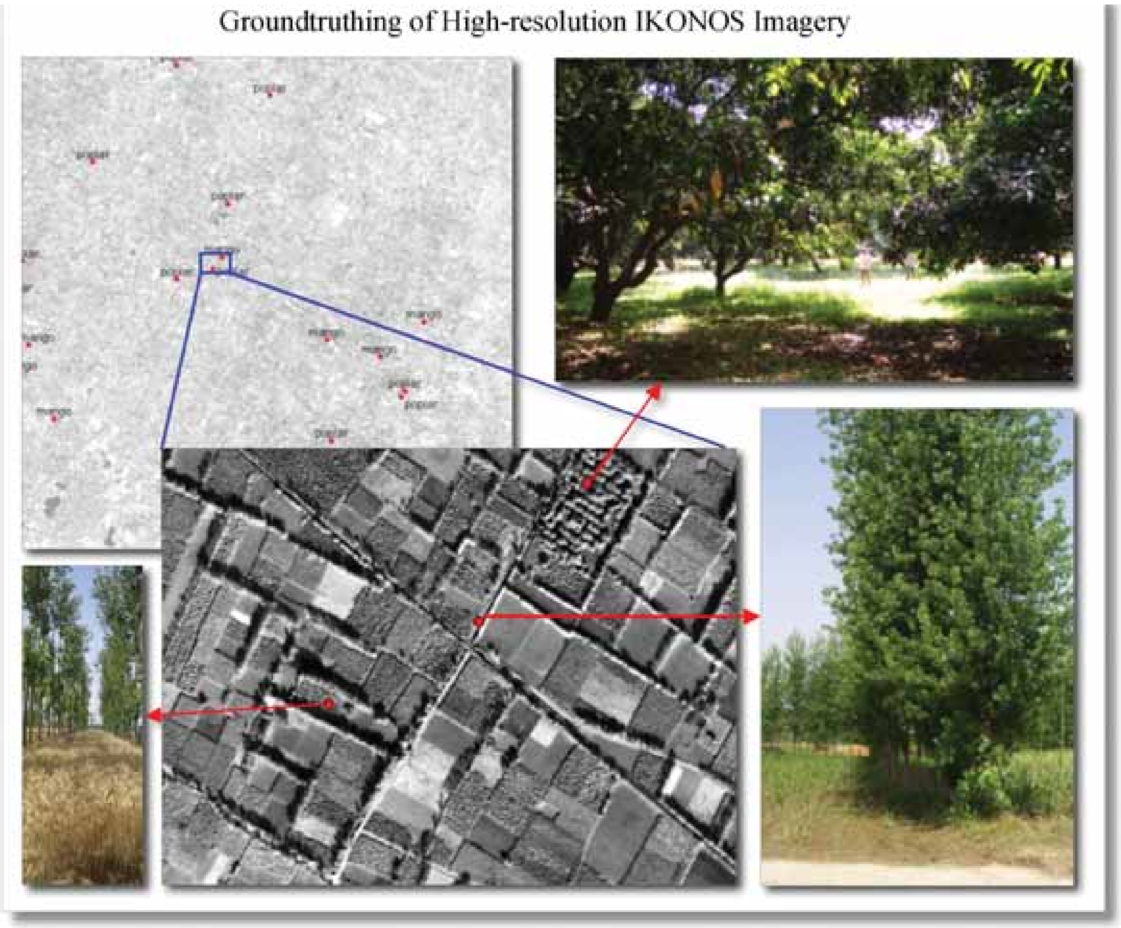


FIGURE 6. Poplar agroforestry, both in block plantings, and boundary plantings on bunds and along roadsides, was identified on a high-resolution (4 m) panchromatic IKONOS image, and used to groundtruth and calibrate the Forest Canopy Density Mapper estimates.

FCD Accuracy Assessment

Detailed plot sampling was carried out on 510 poplar plantations across four districts in Uttar Pradesh State. In 2004, geo-referenced groundtruth data were obtained during the peak of the monsoonal rainy season (October), and at the peak of the dry season (March). Plots with trees older than 3 years were selected for the FCD accuracy assessment (446 plots). In April 2005, a subsequent field campaign was carried out to groundtruth and validate the initial results and to iteratively improve the analysis. Based on these two sets of data, the accuracy assessment of the final maps indicates a relatively high degree of confidence for the identification of areas under agroforestry. Additionally, five test sites for the study area were identified and selected from within a set of publicly available high-resolution images (Google Earth - November, 2006). A one square kilometer area was chosen within a zone containing visible agroforestry, using a random stratified sampling approach. Tree cover within the high-resolution image was manually digitized based on photo-interpretation. Visual assessment confirmed that the FCD analysis compared well with the digitized high-resolution imagery, showing a relatively high average accuracy (within 10%), but with significant variability across the five test sites (Figure 8).

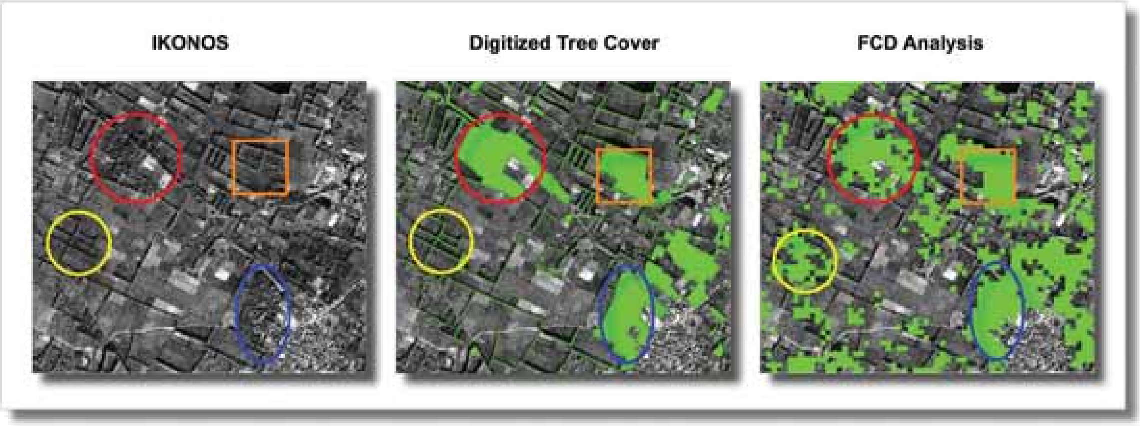


FIGURE 7: Comparison of the results of the Forest Canopy Density (FCD)) analysis with tree cover as manually digitized from the IKONOS panchromatic imagery (4 m).

Water Balance Model

A spatially distributed Thornthwaite-Mather water balance approach (Thornthwaite 1948; Thornthwaite and Mather 1955) was used to examine the hydrologic impacts of trees in irrigated agricultural systems in northeast India. Specifically, the differences in vapor flows and irrigation requirements between a typical cropping system and those systems incorporating poplar agroforestry were examined. The rice/wheat/sugarcane cropping system, which is prevalent in much of the study area, was used as a typical model of an irrigated crop system for this study. It is modeled as an intensive cropping succession with an annual rotation of rice and wheat (grown in the mild winter), along with two successive 13-month rotations of sugarcane over the 10-year rotational cycle. Although most farmers reported irrigating only 6 months of the year (November-April), our model assumes that farmers will irrigate whenever soil moisture becomes limiting. The spatially distributed application of the hydrologic model uses monthly values of precipitation (*Precip*) and potential evapotranspiration (*PET*), and specific crop and interception coefficients for each of the crops grown in the two systems and, returns monthly spatially-distributed data representing actual evapotranspiration (*AET*), irrigation requirements (*Irr*), surface runoff (*R*) and the soil

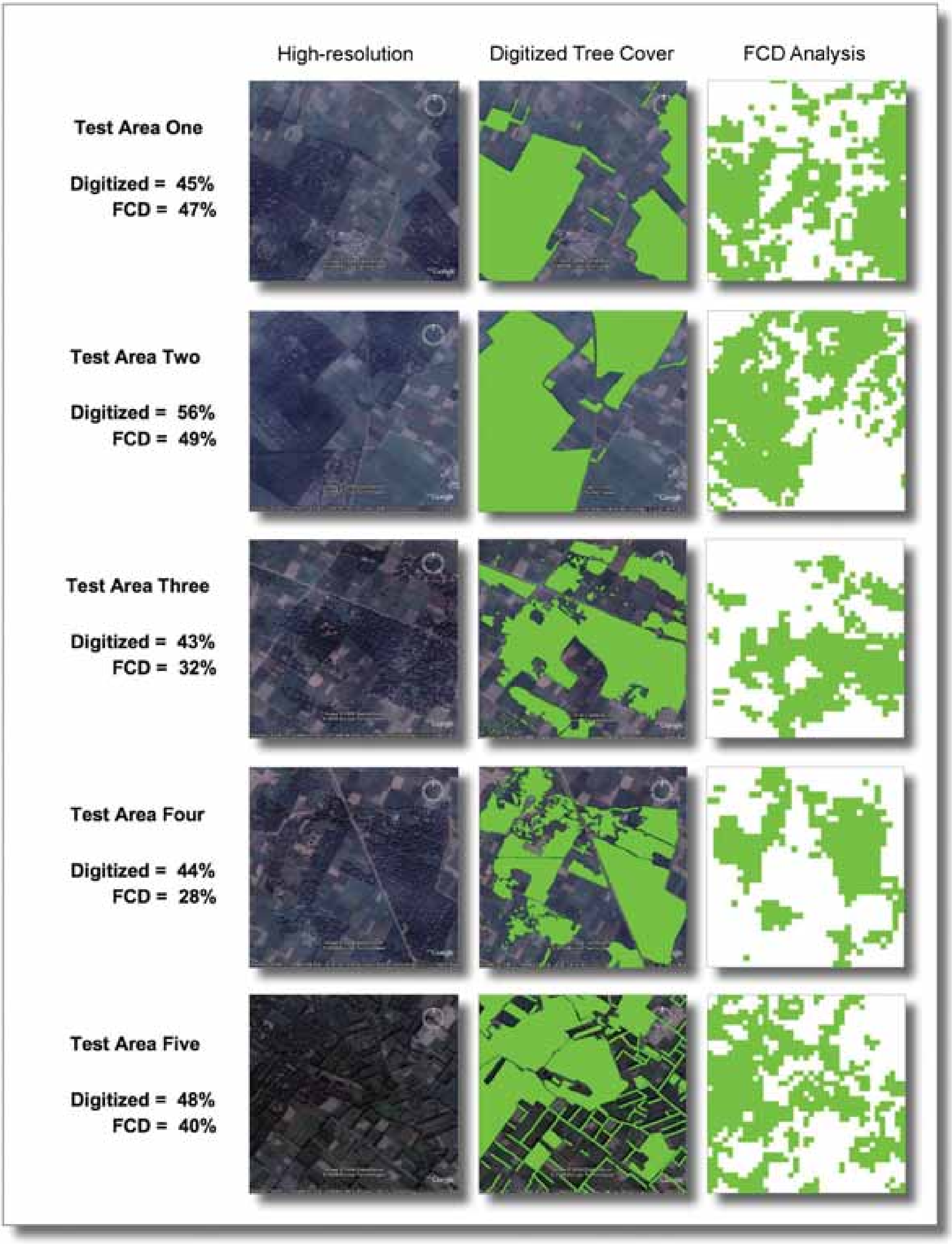


FIGURE 8. Comparison of randomly sampled high-resolution remote sensing imagery (*Source:* Google Earth), with tree cover manually digitized, with the results of the Forest Canopy Density (FCD) analysis.

water content (*SWC*). All the results, both for agroforestry and rice/wheat systems, are computed on a monthly basis over the rotation cycle of 10 years. All the results are aggregated into the average annual figures in order to compare hydrologic differences between the two systems. For each month, the total quantity of water added by irrigation to the system is quantified as the amount required to maintain field capacity throughout the month and to meet all vapor flows.

A soil water balance budget is computed as height of water in mm for each month (m), as:

$$\Delta SWC_m = Eprec_m + Irr_m - AET_m - R_m \qquad mm/month \tag{1}$$

where: ΔSWC_m is the change in soil water content, $Eprec_m$ is the effective precipitation, Irr_m is the irrigation requirement, AET_m is the actual evapotranspiration, and R_m is the runoff component, which includes both surface runoff and subsurface drainage. *SWC* can never exceed a maximum value, SWC_{max}, which is the total *SWC* available for evapotranspiration (*ET).* Therefore, the *SWC* under nonirrigated conditions at the end of the month, SWC_m^f is equal to:

$$SWC_m^f = \begin{cases} SWC_m^b + Eprec_m + AET_m - R_m & \text{if } SWC_m^f < SWC_{max} \\ SWC_{max} & \text{if } SWC_m^f \geq SWC_{max} \end{cases} \tag{2}$$

Irr_m and R_m under nonirrigated conditions are equal to:

$$Irr_m = 0 \tag{3}$$

$$R_m = \begin{cases} SWC_m^b + Eprec_m - AET_m - SWC_{max} & \text{if } SWC_m^b + Eprec_m - AET_m > SWC_{max} \\ 0 & \text{if } SWC_m^b + Eprec_m - AET_m \leq SWC_{max} \end{cases} \tag{4}$$

Under the irrigated conditions of this study then, SWC_m^f, Irr_m and R_m are equal to:

$$SWC_m^f = SWC_{max} \tag{5}$$

$$Irr_m^f = \begin{cases} 0 & \text{if } Eprec_m + SWC_m^b \geq AET_m + SWC_{max} \\ AET_m + SWC_{max} - Eprec_m - SWC_m^b & \text{if } Eprec_m + SWC_m^b < AET_m + SWC_{max} \end{cases} \tag{6}$$

$$R_m = \begin{cases} SWC_m^b + Eprec_m - AET_m - SWC_{max} & \text{if } SWC_m^b + Eprec_m - AET_m > SWC_{max} \\ 0 & \text{if } SWC_m^b + Eprec_m - AET_m \leq SWC_{max} \end{cases} \tag{7}$$

where: SWC_m^b is the soil water content at the beginning of the month. The *SWC* at the end of the month, SWC_m^f, is set as the *SWC* at the beginning of the following month, SWC_{m+1}^b. All the water exceeding SWC_{max} is accounted as runoff (*R*), which also includes groundwater recharge. *R* only occurs during a month when the effective precipitation satisfies the total water requirement and the *SWC* is fully saturated. Given these assumptions, under irrigated conditions, *Irr* and *R* cannot occur simultaneously within the same month, therefore, *Irr* is neglected for the computation of *R*.

Potential Evapotranspiration (PET)

PET is a measure of the ability of the atmosphere to remove water through *ET* processes. Based on earlier investigations, the Hargreaves method of calculating *PET* (Hargreaves et al. 1985; Hargreaves 1994) was chosen to model average monthly *PET* values (Zomer et al. 2006). The Hargreaves method uses mean monthly temperature (T_{mean}), mean monthly temperature range (*TD*) and extraterrestrial radiation (*RA*, radiation on top of atmosphere) to calculate *PET*:

$$PET = 0.0023 * RA * (T_{mean} + 17.8) * TD^{0.5} \text{ (mm/d)} \tag{8}$$

Monthly values for precipitation, and the minimum and maximum mean temperatures were obtained from the WORLDClim dataset (Hijmans et al. 2004) as climatic averages for the period 1960–1990, at a resolution of ~1 km.

An Aridity Index (AI) map was calculated to describe the climate regime of the study area, i.e., not taking into account added water coming from irrigation sources. Aridity Index (AI) is expressed as a function of precipitation, *PET*, and temperature (UNEP 1997):

$$AI = MAP / MAE \tag{9}$$

where:

MAP = mean annual precipitation

MAE = mean annual evapotranspiration.

Monthly values for precipitation and temperature were obtained from the WORLDClim dataset (Hijmans et al. 2004) for 30 years, from 1960–1990, (~1 km) and used to estimate *MAP* and *MAE*. Lower values indicate more arid conditions and higher values indicate more humid conditions.

Actual Evapotranspiration (AET)

Actual Evapotranspiration (*AET*) is the quantity of water that is removed from the soil due to evaporation and transpiration processes (Maidment 1992). *AET* is dependent on *PET*, vegetation characteristics, quantity of water available in the soil and soil-hydrological properties (Allen et al. 1998):

$$AET_m = K_{veg} * K_{soil} * PET_m \quad mm/month \tag{10}$$

where:

K_{soil} = reduction factor dependent on volumetric soil moisture content (0-1)
K_{veg} = vegetation coefficient dependent on vegetation characteristics (0.3-1.3)

The maximum amount of soil water available for ET processes within the plant rooting zone, here defined as SWC_{max}, is equal to the Soil Water Content at field capacity (SWC_{fc}) minus the Soil Water Content at Wilting Point (SWC_{wp}), times the rooting depth.

$$SWC_{max} = RD * (SWC_{fc} - SWC_{wp}) \tag{11}$$

where:

SWC_{max} = maximum soil water content available for ET (mm)
RD = rooting depth (mm)
SWC_{wp} = soil moisture content at wilting point (mm/mm)
SWC_{fc} = soil moisture content at field capacity (mm/mm)

Poplar varieties used in the irrigated agroforestry systems have a particularly shallow rooting system, with about 75% of the rooting mass concentrated in the first 30 centimeters (cm) (Tejwani 1994; Puri et al. 1994). Accordingly, the model assumes that the rooting depth of both poplars and crops is limited to one meter. Average *SWC* at field capacity and wilting point for the study area was chosen based on available literature (Allen et al. 1998).

The soil stress coefficient (K_{soil}) represents the *ET* reduction factor resulting from the limit imposed by the *SWC*. The model uses a simple linear soil moisture stress function that is considered appropriate for monthly computation (Dyck 1983).

$$K_{soil_m} = SWC_m / SWC_{max} \tag{12}$$

SWC_m = soil water content averaged over the month. When the system is irrigated, SWC_m is saturated at field capacity ($=SWC_{max}$) and, therefore, K_{soil_m} is equal to 1.

Effective Precipitation

Rain interception is the process by which precipitation is intercepted by the vegetation canopy (canopy interception losses) and litter (litter interception losses), where it is subject to evaporation. Interception has an important role in the water budget, as it reduces the amount of precipitation available for soil moisture. Effective precipitation (*Eprec*), the part of precipitation that adds moisture to the soil, is calculated as the gross precipitation (*Gprec*) minus the precipitation intercepted by the canopy cover and litter (*Int*). The quantity of rain intercepted is proportional to the interception coefficient K_{int}, specific for different vegetation types, calculated as a fraction of *Gprec*.

Comparative studies between trees and crops show that, under tropical and subtropical precipitation conditions, interception varies between 4% and 14% for crops at a mature stage (van Dijk and Bruijnzeel 2001; Schroth et al. 1999; Waterloo et al. 2000), less than 1% for fallow (Schroth et al. 1999) and 16% to 30% for broadleaves (Kumagai et al. 2004; Waterloo et al. 2000). Based on these observations, an interception coefficient for poplar (*Int_tr*) at full canopy cover has been set equal to 20%, assuming that poplar stands in agroforestry systems are mono-stratified and are likely have interception coefficients which are lower than average for broadleaves. Interception coefficients for each of the crops at average growth stage (*Int_cr*) were set to 6%, which is an average value of fallow and mature stages.

The calculation of specific interception values for the agroforestry system as a combination variable, with the age of poplars and the associated crop, is explained further below.

For each month $Eprec_m$ is calculated as:

$$Eprec_m = Gprec - Int \tag{13}$$

where: Int is equal to:

$$Int = (Gprec * K_{int}) \tag{14}$$

Therefore:

$$Eprec_m = Gprec - (Gprec * K_{int}) = Gprec * (1 - K_{int}) \tag{15}$$

We combine the *AET* and *Int* components of the model to quantify ‘green water’ vapor flows, i.e., the portion of precipitation that evaporates to the atmosphere, and is not available as runoff.

Crop Coefficient for Poplar

The crop coefficient (K_{veg}) for poplars $(K_{veg\_tr_m})$ is equal to 1 (i.e., the maximum value of $(K_{veg}$, or $K_{veg\_max})$ when the poplar plantation is at full canopy cover, i.e., after the third year of the rotation (Allen et al. 1998; USBR 2006). K_{veg} of poplar increases linearly from 0 to 1 in the first 3 years (USBR 2006), based on an increase in canopy cover from 0 to 100% in those first 3 years. Poplars are senescent (i.e., have no canopy cover) during the months of January and February. We assume, therefore, that during the annual cycle, the K_{veg} value decreases linearly from 1 to 0 during the month of December, equals 0 during the dormant season (January and February) and then increases linearly from 0 to 1 during the month of March.

For each month (m) in the rotation period $K_{veg\_tr_m}$ is equal to:

$$K_{veg\_tr_m} = K_{veg\_tr_{max}} * Tr\_leaf\_cov_m / 100 \tag{16}$$

where:

$K_{veg\_tr_{max}}$ is equal to the maximum value of $kveg$ for poplar $(K_{veg\_tr_{max}} = 1)$

$TR\_leaf\_cov_m$ is equal to the average monthly tree leaf coverage, in percentage.

Typically, when vegetation transpiration is low or nil, K_{veg} should still be equal to values of about 0.4, to include soil evaporation (Allen et al. 1998). However, when the poplar canopy is low, or when the poplar is senescent, associated intercrops are grown, and ET is mainly regulated by the K_{veg} of the complementary intercrop.

Crop Coefficients for Crops

The poplar agroforestry is compared to a simple cropping system modeled with a rotation of winter wheat and rice, and two successive rotations of sugarcane (original plus a ratoon crop) over the same period as the poplar rotation. The growing period (Figure 9) of any crop can be divided into four distinct growth stages (Allen et al. 1998). Each one of these four stages is characterized by the three specific crop coefficients (K_{veg_ini}, K_{veg_mid} and K_{veg_end}), which together with the length of the growth stages allow the calculation of K_{veg} throughout the cropping cycle. Crop coefficient values for rice, wheat, and sugarcane (Figure 10) at the different growth stages (Table 1), and the length of each growth stage (Table 2), were obtained from Allen et al. (1998).

Wheat is planted at the beginning of the *Rabi* season (November) and rice at the beginning of the *Kharif* season (May). Sugarcane, however, is planted throughout the year, usually within one to two months after harvesting the previous crop. The full 10-year cycle of the rice/wheat/sugarcane rotation is modeled based on each crop's annual (or biannual) cycle.

Crop Coefficients for the Poplar Agroforestry System

We assume that the quantity of associated intercrops that grow under the poplar trees is complementary to the tree leaf coverage of the poplar plantation. Therefore:

$$K_{veg\_cr\_comp_m} = K_{veg\_cr_m} * (1- [Tr\_leaf\_cov_m /100]) \tag{17}$$

where:

$K_{veg\_cr_m}$ equals the K_{veg} of the complementary crop grown in the month (m), if planted alone, i.e., using 100% of available resources.

$K_{veg\_cr\_comp_m}$ equals the K_{veg} of the complementary crop when intercropped with poplar in the month (*m*), i.e., using resources not used by the poplar.

In our representative model of the poplar agroforestry system, sugarcane is grown during the first 27 months. After month 27, wheat is grown annually during the *Rabi* season (November to April) when poplars are senescent (Jha 1999), and rice is grown in the *Kharif* season (May to October).

The total K_{veg} of the agroforestry system is then equal to:

$$K_{veg\_tot_m} = K_{veg\_tr_m} + K_{veg\_cr\_comp_m} \tag{18}$$

The K_{veg} of the agroforestry system (Figure 11) is compared with the rice/wheat/sugarcane cropping rotation over a 10-year rotation cycle (Figure 12).

Interception Values for Agroforestry and Crops

Specific interception values for the agroforestry system have been calculated as a weighted average value, based on the percentage of canopy cover of poplar and the associated crop. The interception coefficient for the poplar agroforestry system during the month *m* (Int_af_m) is equal to:

$$Int\_af_m = (Int\_tr * Tr\_leaf\_cov_m/100) + (Int\_cr * (1 - (Tr\_leaf\_cov_m/100))) \tag{19}$$

Interception coefficient for poplar (*Int_tr*) has been set as equal to 0.20, with the interception coefficient for each of the crops (*Int_cr*) set as 0.06, based upon available literature, as above.

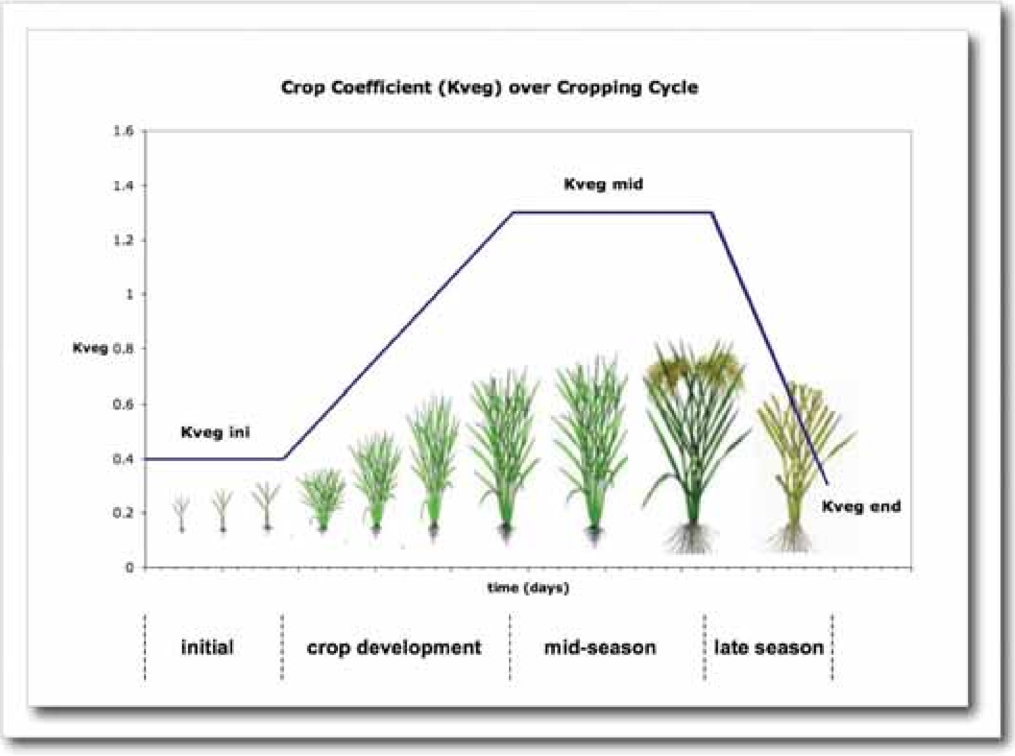


FIGURE 9. Crop coefficient (Kveg) values over the crop growth cycle, and a delineation of the various growth stages. (*Source:* Allen et al, 1998).

TABLE 1. Crop coefficient values at the different growth stages for sugarcane, winter wheat and rice. *Source:* Allen et al. 1998.

Crop Growth Stage Coefficient

	K_{veg_ini}	K_{veg_mid}	K_{veg_end}
Sugarcane	0.4	1.25	0.75
Winter Wheat	0.4	1.15	0.4
Rice	1.05	1.2	0.75

TABLE 2. Length of growth stages (number of days) for sugarcane, winter wheat and rice. *Source*: Allen et al. 1998.

Crop Growth Stages (days).

	Initial (days)	Crop Development (days)	Mid-season (days)	Late Season (days)	Total (days)
Sugarcane	50	70	220	140	480
Sugarcane Ratoon	30	50	180	60	320
Winter Wheat	20	60	70	30	180
Rice	30	30	60	30	150

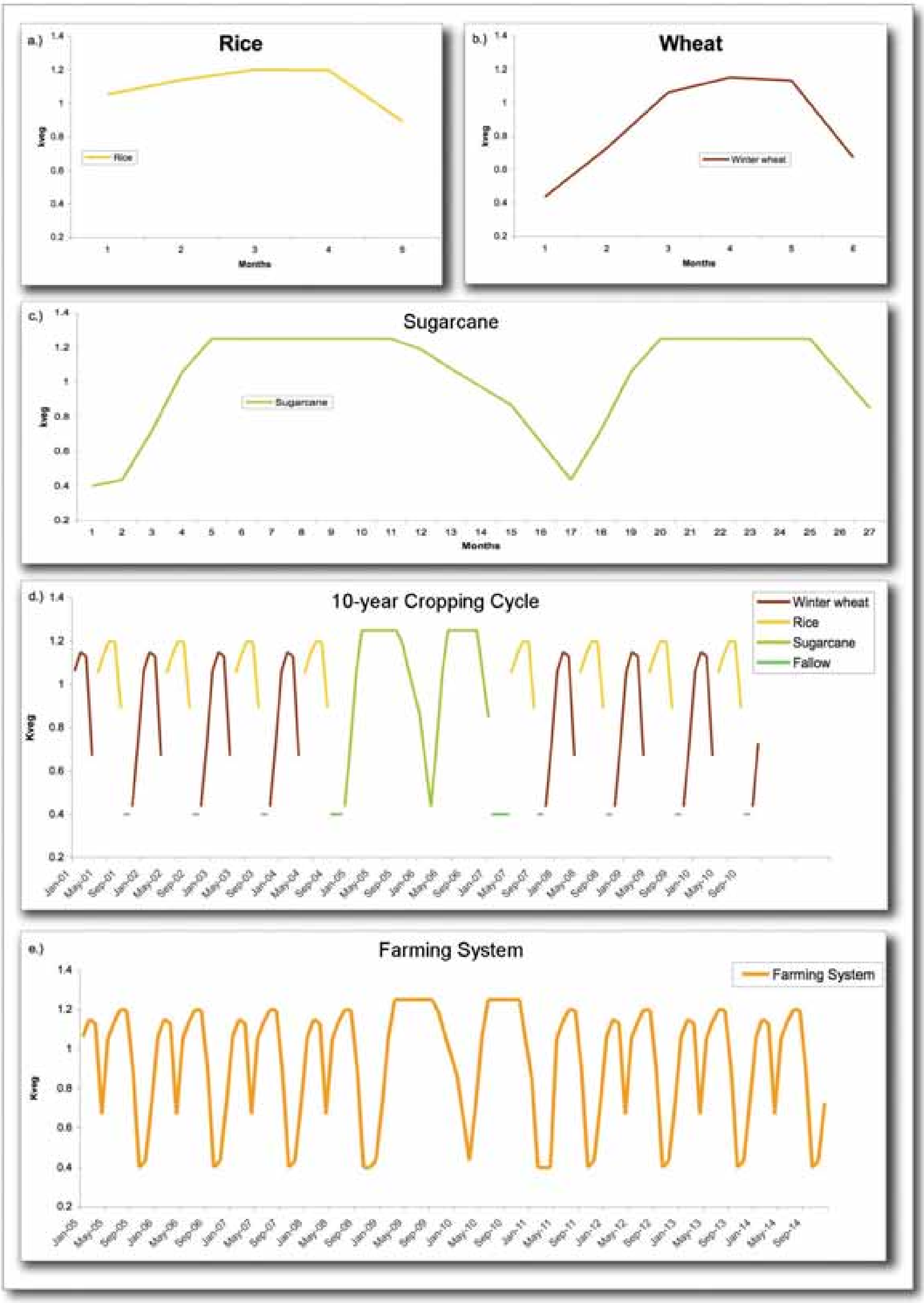


FIGURE 10. The crop coefficient (Kveg) for rice, wheat, sugarcane, the 10-year cropping cycle, and the overall farming system are shown in the figure, as used in the model. *Source:* Allen et al. 1998.

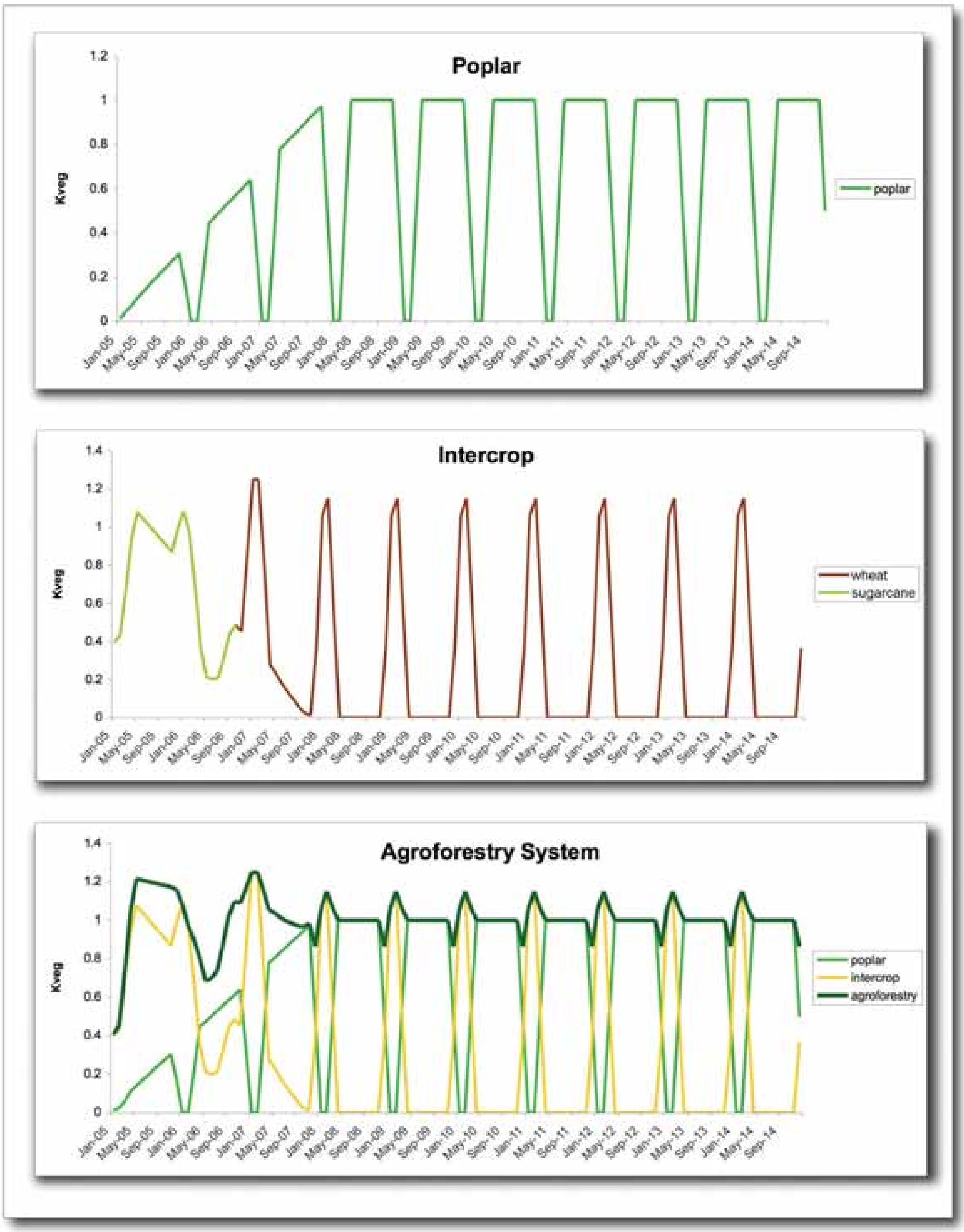


FIGURE 11. The crop coefficient (Kveg) for poplar, the intercrop cropping component, and the overall agroforestry system (i.e., poplars + intercrop) are shown in the figure, as used in the model.

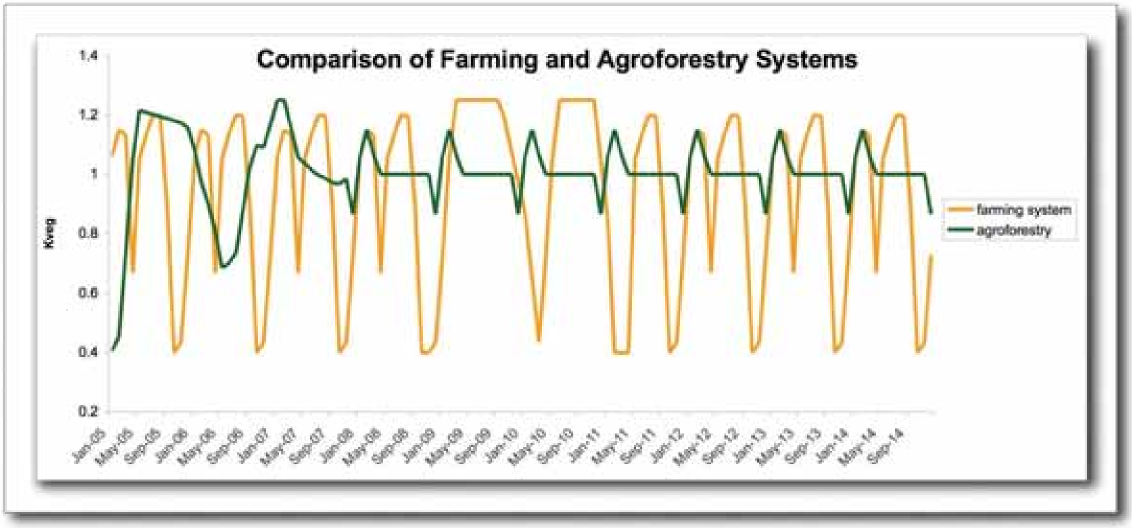


FIGURE 12. The crop coefficient (Kveg) time series for the agroforestry system (i.e., poplars + intercrop) is compared with the rice-wheat-sugarcane 10-year rotation (farming system) in the figure, as used in the model.

Results and Discussion

Field Survey

The majority of the farmers interviewed (60%) belong to the category of marginal and small farmers, i.e., having only up to 2 ha of land. The average size of the farm-holding of all the 508 farmers interviewed is 2.2 ha, but it varies from district to district. Almost 26% of the farmers in the study had farm-holdings of less that 0.5 ha of land. On average, farmers who have taken up poplar in block plantings have allocated about 30% of their total farm-holdings for growing trees.

The socioeconomic analysis revealed that a majority of the farmers (57%) are within the 'average' socioeconomic class (of farmers), and most of the rest (41%) were found to be relatively affluent. Rai et al. (2001) found that adoption increased as farm-holding size increased, with all farmers who had large holdings adopting. Poplar agroforestry provided significant additional income per hectare to farmers (Gupta et al. 2005), as well as creating employment opportunities on farms (Jain and Singh 2000). Additionally, the large quantity of wood produced annually through poplar agroforestry helps to meet the growing demand for wood in the match, pulp and plywood industries (Figure 13), generating significant additional employment in the area (Dhillon et al. 2001). These findings agree with assessments that found poplar agroforestry to be economically viable and more profitable than many of the crop rotations found in the study area (Jain and Singh 2000; Dhillon et al. 2001; Singh et al. 2001). Returns from intercrops contributed significantly to that profitability, generally providing income sufficient to breakeven on the farm's annual costs, but with declining yields as the tree canopy becomes denser. Nearly all studies of net present value of poplar agroforestry show an improvement over poplar monoculture (Dhukia et al. 1989; Jaswal et al. 1993; Newman 1997). Sharma and Singh (1992) carried out one of the few studies on bund planting, with similar results.

More recently, however, low prices have impacted that positive profit ratio (Gupta et al. 2005), with many farmers reporting that either they were waiting an additional year to harvest, or not

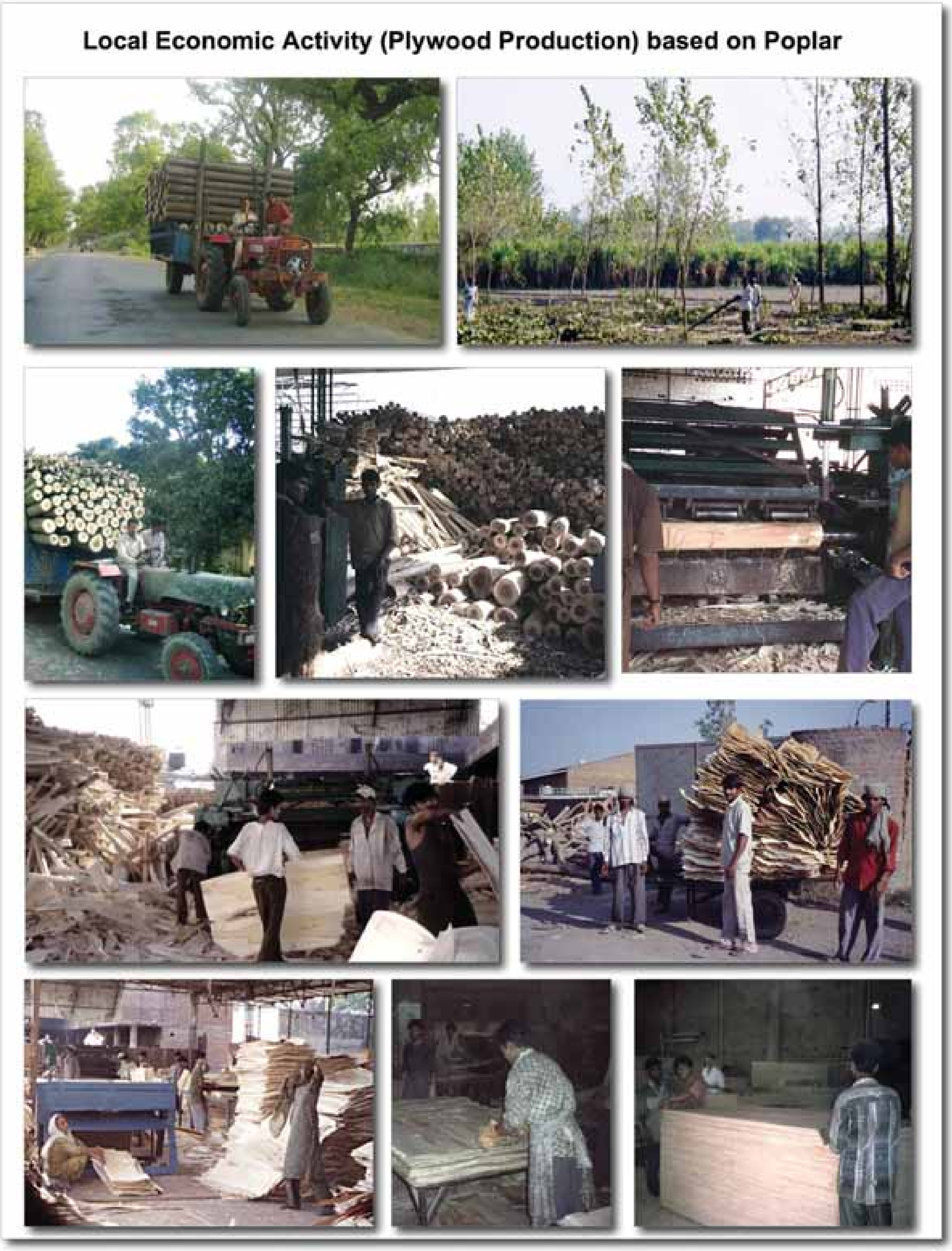


FIGURE 13. Poplar production contributes substantially to local economic activity in the area. There are more than 350 small-scale plywood factories within the area, as well as industrial demand for pulpwood and matchsticks.

replanting. This result highlighted the need for improved marketing arrangements to improve the economic security of small producers. However, demand for wood, both in India and globally, will continue to increase, so that market response by farmers should once again lead to a situation where prices are higher. Singh and Marzoti (1996) reported a shortfall of more than 20 million cubic meters (m^3) of industrial timber in meeting the demand of wood industries in India, resulting in large amounts being spent yearly on imports. Demand for industrial wood is rapidly increasing and projected to rise to 100 million m^3 by 2050 (Singh et al. 2001). Similarly, the demand for firewood was estimated at 201 million tons versus a supply of 98 million tons, leaving an expected unmet demand of 103 million tons (Rai and Chakrabarti 2001).

All the land of the selected farmers had access to irrigation. The majority of these lands are irrigated by private tube wells (81%), some by canal irrigation (13%), with the other 6% relying on canals (with supplemental irrigation from private tube wells). The EC, a measure of the amount of dissolved salts in the irrigation water in the selected districts/villages, was found to be between 0.1 and 2.5. Only a few water sources, in the districts of Aligarh and Saharanpur, have an EC value more than 1.0, i.e., indicating moderate salinity. Most of the farmers (86%) irrigate their poplar plantations during April to June, when the atmospheric temperature is high with a low level of relative humidity (mostly by flooding the fields). Farmers stated that they provide irrigation depending on need, with the required frequency varying from 30 to 45 days. This is less than what is reported by Hara (2004), who states that weekly irrigation is required during the dry months for high intensity production (Figure 14). During the early stages of the plantation, irrigation is provided at an interval of 20 to 25 days. The majority of farmers interviewed felt that groundwater levels have been stable for the past 10 years, with around 40% of farmers reporting a decline during the past 5 years. Data collated from the UP State groundwater records indicate that there has been no significant depletion in the groundwater level within the selected blocks during the past 10 years (Gupta et al. 2005).

According to the observations of the survey, food security was not a major issue for the poplar growers. India has quadrupled its grain harvest over the past 50 years to reach the current level of 210 million tons per annum (Singh et al. 2001). This remarkable growth rate in the grain harvest was achieved mainly through irrigation development, farm capitalization and increasing use of inputs. Farms in this area, though small in size, are highly commercial with farmers having good market access. The majority of the growers across all farm sizes were found to sell significant quantities of food grains. The data indicate that 72% of the paddy, 62% of the wheat, and 80% of the pulses produced by these farmers are sold in the market. In general, economic security was enhanced, and risk reduced through the diversification into poplar production. This was especially true for bund plantings, and poorer farmers planting farm margins, where earnings can be significantly increased with little or no impact on crop production (Sharma et al. 2001). This is partly due to the very high productivity of poplar within the study area (Singh et al. 2001), which makes boundary plantings worthwhile even for smallholders. Bund and boundary plantings, found to be widely adopted within the study area, provide income and equity growth with very little cost in terms of either land or labor.

How Much Agroforestry?

There is little accurate information identifying the areal extent of poplar agroforestry in the region. Progress reports prepared by WIMCO provide indications of the extent of adoption in the region, based on the number of seedlings distributed and the number of farmers enrolled in their programs. Singh et al. (2001) reported 30 million poplar trees in Uttar Pradesh, Haryana, Punjab, Himachal Pradesh and Jammu and Kashmir, producing 1,125 million m^3 of industrial wood annually. At 500 trees per ha, this is the equivalent of only 60,000 ha across the region. However, it is also reported that 25,000 ha equivalent of new plantations per year were being established during this period, based on the distribution of 13 million trees

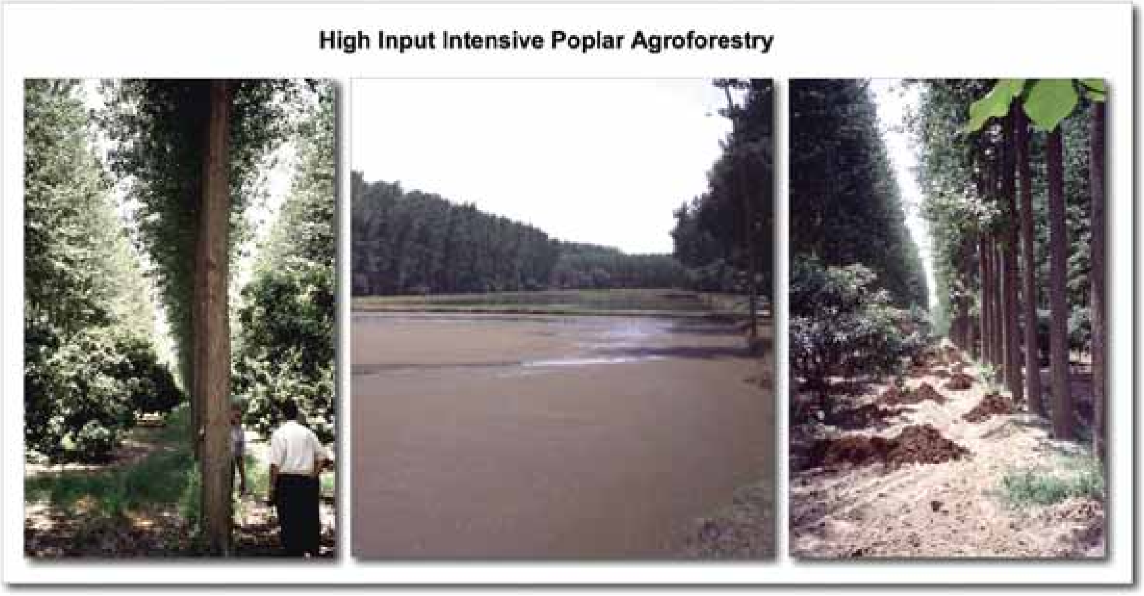


FIGURE 14. High growth rates and high timber values for poplar are achieved using modern farming approaches, including inputs of nutrients and water. The figure shows an example of a best practices input and management intensive approach developed by Surinder Singh Hara in Haryana State, including application of fishpond sludge and urea to promote fast growth and high-value productivity.

annually by plantation agencies, farmers and NGOs. It is stated that during the Government of India's Eighth Five-Year Plan, the agricultural area brought under poplar agroforestry was equal to the extent of forest plantations established by the forest departments in those states (Chandra 2001). Likewise, the number of farmers engaged (in varying degrees) in planting poplars is purported to be large, constituting a large portion of all farmers in the area. A sustained growth rate from the 1980s until very recently is readily apparent in the landscape.

TABLE 3. Estimated area of agroforestry within the study area, using various levels of canopy cover as the threshold for the agroforestry class, based on the Forest Canopy Density (FCD) Mapper remote sensing analysis.

FCD Estimated Agroforestry Area across a range of Threshold Values

Agroforestry (% of Irrigated Area)	Canopy Cover FCD Threshold (%)	Area (ha)
0	n/a	0
5	99	138,962
10	75	283,321
15	49	443,491
20	30	576,086
25	1	716,417
50	0 *	1,454,160
100	0 **	2,885,777

* All areas above a FCD threshold value of 0 plus 1/3 of remaining area randomly chosen

** All irrigated agricultural areas

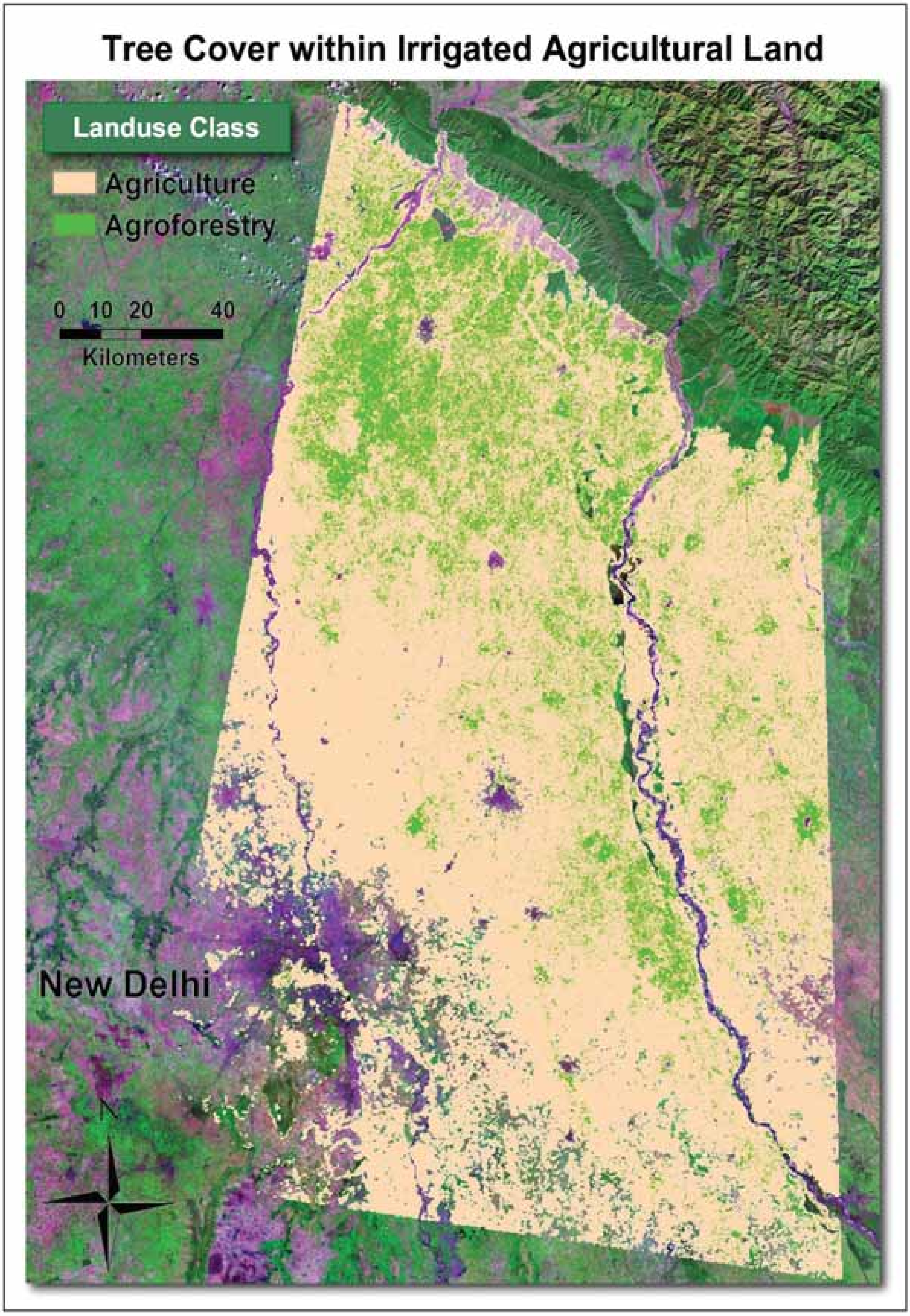


FIGURE 15. Areal extent of agroforestry was identified using the Forest Canopy Density (FCD) Mapper algorithm. The map above, showing agroforestry in green and agriculture in light yellow, is based on a 75% canopy cover threshold (per pixel), which results in agroforestry being present on 9.8% of all irrigated lands with the study area.

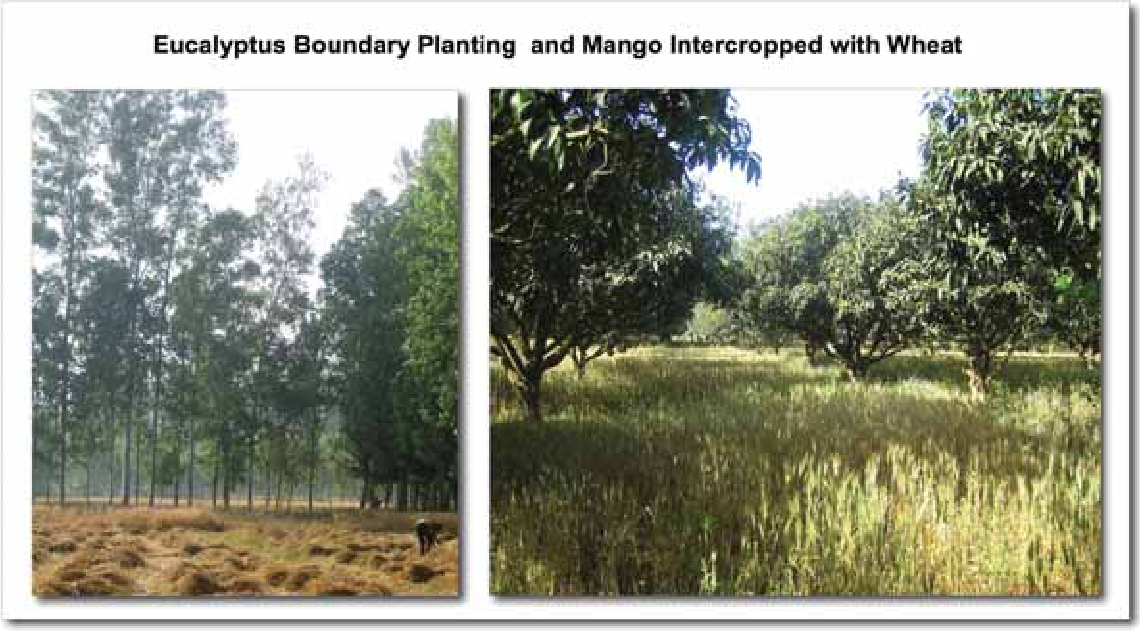


FIGURE 16. Eucalyptus, mango and other tree crops are commonly grown throughout the region, contributing to the high tree cover found in this agricultural landscape. Many of these are also found intercropped with staple crops in agroforestry type approaches.

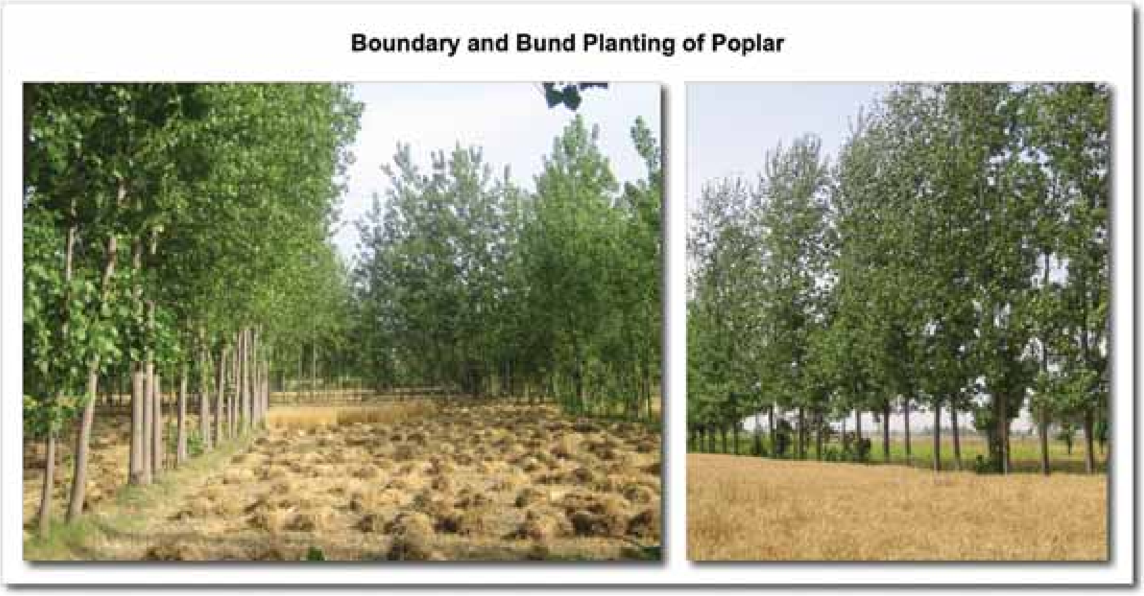


FIGURE 17. Poplar is commonly found planted along boundaries, on bunds, and lining water ditch, canals and roads.

The FCD analysis mapped the tree cover on the 2.9 million ha of irrigated agricultural land within the study area. The range of potential agroforestry area is 5% of the landscape if 99% tree cover is used for the agroforestry threshold, to 25% of all agricultural lands at a threshold of 1% tree cover (Table 3). Based on the evaluation of IKONOS and groundtruth data, a tree cover > 75% (i.e., within pixel) was chosen as the threshold to delineate agricultural land into agroforestry and non-agroforestry classes. At this value, roughly 280,000 ha, or just under 9.8% of the irrigated agricultural area, was identified as being under agroforestry (Figure 15). The high-resolution imagery revealed that the majority of tree plantings are on bunds and borders, rather than in blocks. However, as this estimate includes all tree cover, it represents a significant overestimate of the area under poplar agroforestry. Significant areas of mango, citrus, and other orchard crops, and some eucalyptus are likely included in the agroforestry category (Figure 16). Nevertheless, the analysis indicates widespread adoption of the poplar agroforestry system by farmers within this area. In particular, the cumulative impact on regional tree cover of widespread and dispersed boundary and bund plantings (Figure 17) on a large-scale throughout this agricultural landscape, is the tree cover equivalent to that of woodland savannahs and dry forests.

Hydrologic Impact of Agroforestry in Irrigated Areas

Regional Climatic Spatial Variability

The Ganges Basin is subject to a monsoonal climate regime, with a large proportion of its annual precipitation occurring within the summer months. A wide range of values for the temperature and precipitation is combined with a high spatial variability along a gradient from south to north across the study area (Figure 18). Although the mean precipitation value is 949 mm (Table 4), precipitation ranges from 490 mm in the dry south to 1,827 mm near the Himalayan foothills. *PET* (mean = 1,665 mm) is relatively high, reflecting a generally warm sunny climate with very high temperatures before the onset of the monsoon. Climatic variables were analyzed using an *AI* modeled spatially to quantify precipitation deficit over atmospheric water demand (Allen et al. 1998). In an earlier global study of hydrologic impact of afforestation, optimal bioclimatic zones for afforestation and reforestation were found to be above the threshold of *AI* = 0.65 (Zomer et al. 2006). This value approximates the lower threshold for a semi-arid moisture regime that can support rain-fed agriculture with more or less sustained levels of production (UNEP 1997). More than 82% of the study area has an *AI* below 0.65, indicating the severity of water scarcity for agricultural production in this region, before the investment in a widespread irrigation infrastructure.

Regional Increases in Vapor Flows

The annual AET predicted for the agroforestry system (Figure 19) ranges from 1,781 to 1,940 mm, with a mean of 1,839 mm (Table 5). This compares with a regional mean of 1,684 mm (Table 6). The increase in annual AET resulting from agroforestry averages around 177 mm, roughly a 10% increase in annual vapor flows, with maximum values being as high as 16%. This is in agreement with a Sharma et al. (2001) study on boundary plantings of poplar adjacent to wheat, which showed an increase in water use from 7.5 to 12.7% in 4-year old plantations along a gradient from the tree line to the adjacent crop. In the case of our model, results are based on an idealized

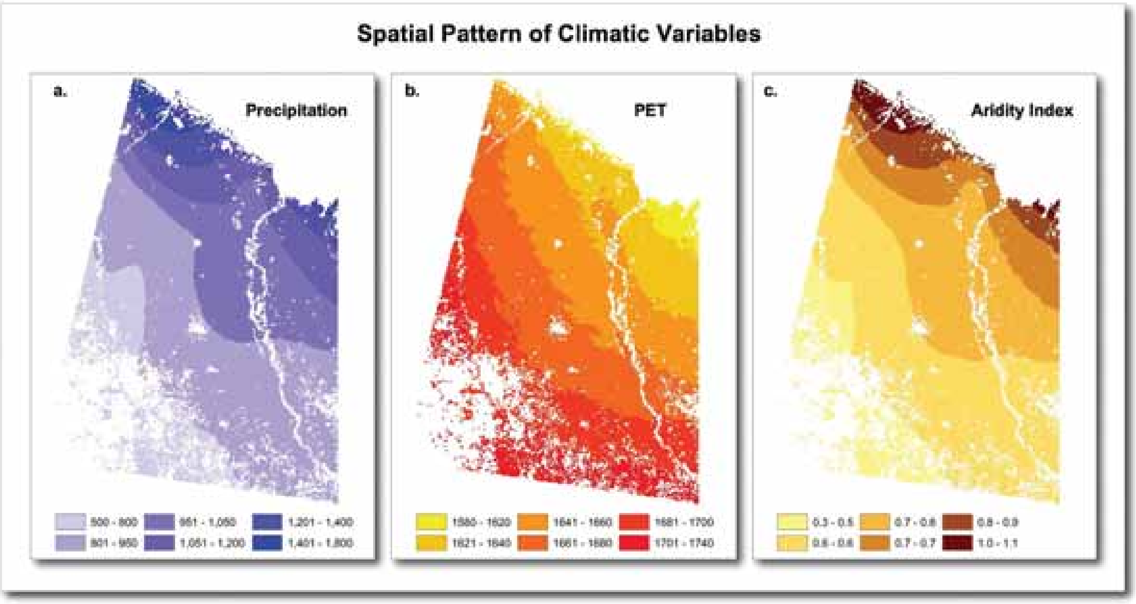


FIGURE 18: Climatic variables used in the hydrologic analysis included precipitation (*Prec*), potential evapotranspiration (*PET*), and an aridity index (*AI*).

TABLE 4. Mean and range of values for the climatic variables within the study area, as used in the spatial analysis and hydrologic modeling. *Data Source:* Hijmans et al. 2004

Climate Variables

		Mean	Min	Max	Std
Precipitation	(mm)	949	490	1,827	175
PET	(mm)	1,665	1,575	1,736	25
Aridity Index		0.57	0.29	1.13	0.11

TABLE 5. Current annual vapor flow (*AET*) and annual irrigation requirement (*Irr*), and increase resulting from the adoption of agroforestry, on all lands identified as existing agroforestry.

Annual Vapor Flow (*AET*) and Annual Irrigation Requirement (*Irr*) within Agroforestry Area

	Mean	Min	Max	Std
Agroforestry Area = 9.8%	(mm)	(mm)	(mm)	
Annual Vapor Flow (*AET*)	1,839	1,781	1,940	18
Annual Vapor Flow Increase (mm)	177	130	245	13
Annual Vapor Flow Increase (%)	10.6	7.8	14.5	0.8
Annual Irrigation Requirement (*Irr*)	1,039	836	1,325	54
Annual Irrigation Requirement Increase (mm)	141	130	167	5
Annual Irrigation Requirement Increase (%)	15.8	11.2	19.3	1.1

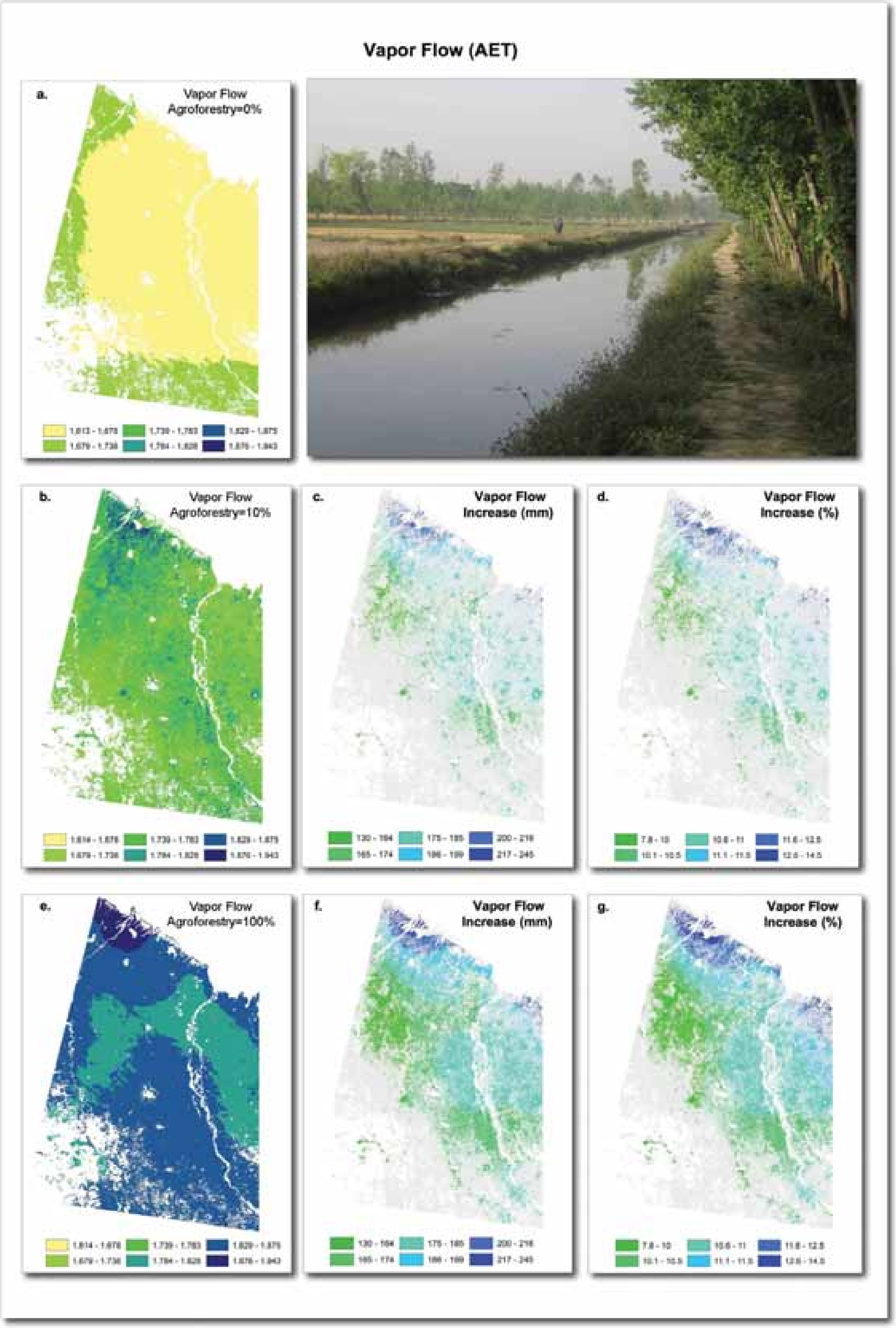


FIGURE 19. Predicted vapor flow is shown at three levels of agroforestry, including (a) if there was no agroforestry, and (b) at the existing current estimate of extent. The increase in vapor flow is shown as both (c) an absolute (mm) increase (d) and a relative (%) increase. Predicted vapor flows with conversion of all irrigated areas to agroforestry highlights the spatial variability of (e) irrigation requirement, and the variability between (f) absolute increase and (g) relative increase.

TABLE 6. Annual Vapor Flow (*AET*) for the entire agricultural landscape at various levels of adoption of the poplar agroforestry system.

Annual Vapor Flow

Agroforestry (% of Irrigated Area)	Mean (mm)	Min (mm)	Max (mm)	Std (mm)
0	1,666	1,613	1,707	15
10	1,684	1,614	1,940	53
15	1,693	1,614	1,941	64
20	1,702	1,614	1,941	70
25	1,710	1,614	1,941	75
50	1,754	1,614	1,942	87
100	1,839	1,780	1,942	17

Annual Vapor Flow Increase (mm)

Agroforestry (% of Irrigated Area)	Mean (mm)	Min (mm)	Max (mm)	Std (mm)
0	0	0	0	0
10	18	0	245	53
15	28	0	245	64
20	36	0	245	71
25	44	0	245	76
50	88	0	258	87
100	173	130	172	15

Annual Vapor Flow Increase (%)

Agroforestry (% of Irrigated Area)	Mean (%)	Min (%)	Max (%)	Std (%)
0	0.0	0.0	0.0	0
10	1.1	0.0	14.5	3
15	1.7	0.0	14.5	4
20	2.1	0.0	14.5	4
25	2.6	0.0	14.5	5
50	5.3	0.0	15.6	5
100	10.4	7.7	15.6	1

crop rotation over a 10-year cycle, so that the estimates are calculated as an average value of annual AET over the 10-year rotation period. This assumption is used to scale-up the model to incorporate the fact that the poplar identified within the landscape as agroforestry could be at any point along that 10-year time cycle (but likely to be at least 3 years old if identified by the FCD analysis). High levels of AET occur only during the last half to two-thirds of the 10-year rotation, and only during full leaf and not during winter dormancy. As a result, the average values reflect the negligible contribution of poplar to annual AET during the early years of the agroforestry rotation. The equivalent mean annual increase in AET across the entire agricultural zone resulting from agroforestry, with agroforestry extent at the current 10% of agricultural area, is only 18 mm, i.e., a mere 1.1% of annual vapor flows. Even with full adoption, that is, even if the entire agricultural area adopted agroforestry, the total increase in annual vapor flows would still only be 10.4%.

Since poplars and various other trees grow rapidly and transpire large amounts of water, hydrological effects of poplar-based agroforestry and other tree-based systems are, in general, expected to be significant with potential consequences for adjacent crop production (Rao et al. 1998) and downstream users. Generally, non-orchard trees within the agricultural landscape are viewed as using water in situ, directly competing with agricultural production and/or lowering overall water use efficiency. Poplar agroforestry presents a different set of circumstances, in that it is planted on irrigated land, either replacing or complementing a high input, intensive, irrigated rice/wheat cropping system. The relatively minor increase in the vapor flow associated with the conversion to agroforestry is further diminished at the landscape level, with only 10% of land currently under agroforestry. As a result, the increased vapor flow across the region resulting from the adoption of agroforestry is estimated to be minimal, although locally it can range as high as 16%. The deciduous phenology of poplar contributes considerably to its low impact on water use, with a dormancy period that corresponds with the peak growth of the winter (or dry season) crop. Likewise, this deciduous phenology minimizes the annual AET, and particularly reduces the irrigation requirement of the poplar component within the farming system.

Regional Increase in Irrigation Requirement

The annual irrigation requirement (*Irr*) for the entire area was estimated, both with and without agroforestry (Figure 20). *Irr* is the amount of irrigation water needed per year to maintain AET under non-water stress soil moisture conditions, i.e., at or near field capacity, throughout the year, supplemental to the amount received through precipitation. The impact on *Irr* of a shift to poplar agroforestry is dependent on the increase in AET, but mitigated by the precipitation which that site receives. The absolute amounts of *Irr*, as given in mm, tend to roughly vary along with *AI*. In drier areas that already require substantial irrigation for crop production, relative increases may be fairly minimal. However, areas that do not require as much irrigation for cropping may see larger relative increases with a shift to poplar agroforestry. Consequently, absolute values for *Irr* (mm) and relative increases (%) vary differentially based on the relative dependence on irrigation for crop production. Areas with higher precipitation also have relatively higher increases in interception losses with agroforestry.

The mean Irr for the total area under poplar agroforestry was estimated at 1,039 mm, whereas the mean *Irr* for the entire study area if under agricultural production, was estimated at 924 mm, an increase of 141 mm (Table 7). This represents approximately a 16% increase in *Irr* on lands converted to agroforestry. A gradient of spatial variation across the study area identifies higher impact regions where *Irr* increases to 20% (167 mm) of additional water. Likewise, regions where increases are minimal are also identified.

The mean value for *Irr* when averaged across the entire landscape, including both agricultural and agroforestry areas is estimated at 938 mm (Table 7). This represents a relatively minimal increase of 14 mm, or 1.6%, when comparing existing landuse, including land currently under agroforestry

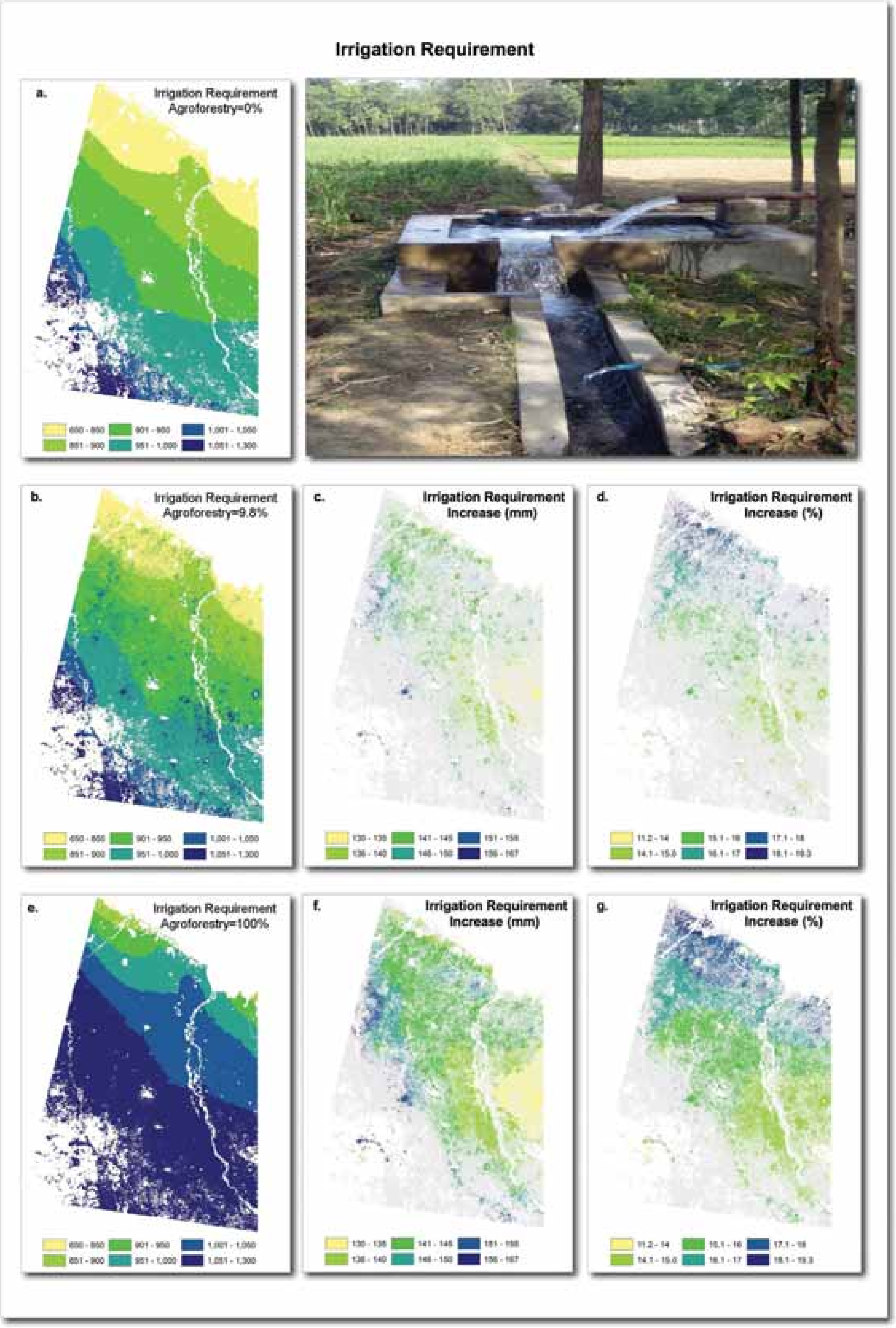


FIGURE 20. Irrigation Requirement (*Irr*) is shown at three levels of agroforestry, including (a) if there was no agroforestry, and (b) at the existing current estimate of adoption. The increase in *Irr* is shown as both (c) an absolute (mm) increase (d) and a relative (%) increase. Predicted vapor flows with conversion of all irrigated areas to agroforestry highlights the spatial variability of (e) irrigation requirement, and the variability between (f) absolute increase and (g) relative increase.

TABLE 7. Annual Irrigation Requirement (*Irr*) for the entire agricultural landscape at various levels of adoption of the poplar agroforestry system.

Annual Irrigation Requirement (*Irr*)

Agroforestry (% of Irrigated Area)	Mean (mm)	Min (mm)	Max (mm)	Std (mm)
0	924	668	1,210	70
10	938	669	1,325	77
15	946	669	1,325	80
20	952	669	1,329	81
25	960	669	1,329	82
50	997	669	1,346	95
100	1,068	796	1,346	74

Annual Irrigation Requirement Increase (mm)

Agroforestry (% of Irrigated Area)	Mean (mm)	Min (mm)	Max (mm)	Std (mm)
0	0	0	0	0
10	14	0	167	42
15	22	0	167	51
20	29	0	167	57
25	45	0	167	61
50	73	0	169	72
100	144	128	169	7

Annual Irrigation Requirement Increase (%)

Agroforestry (% of Irrigated Area)	Mean (%)	Min (%)	Max (%)	Std (%)
0	0.0	0.0	0.0	0.0
10	1.6	0.0	19.3	4.7
15	2.5	0.0	19.3	5.7
20	3.2	0.0	19.7	6.3
25	4.0	0.0	19.7	6.9
50	8.0	0.0	19.7	7.9
100	15.7	11.1	19.7	1.1

(9.8%), to an estimated *Irr* for the entire agricultural landscape without any agroforestry. Considering the contribution of poplar to the local economy and farmer livelihoods, this represents a relatively low-cost improvement in productivity when evaluated in terms of water use. Results indicate that the widespread adoption of poplar agroforestry has created an improvement in the water productivity of this region. The high spatial variability found in the results of the analytic modeling highlights the potential use of this modeling approach by landuse managers, for example, to assess the impact of promoting new plantations within specific regions and areas.

The modeling approach was cost-effective and timely, however, would benefit from validation and calibration of results through hydrological fieldwork. Preliminary comparison with global data sets of runoff showed a good correspondence with the model results. Future efforts should calibrate this modeling approach with water use measurements, e.g., using sap flow devices, or ground measurements of water use, to improve validation and calibration of results, both locally and globally.

Conclusion

The relation between trees and water continues to be a ‘hot topic’ of public and scientific debates. This is, especially true in India, where the emergence of a powerful environmental lobby has initiated an ongoing debate on the hydrological effects of agroforestry and other tree-based systems (Puri and Nair 2004). In particular, the effect of trees on water yields has been the subject of much discussion. Nevertheless, results from both our field study and the remote sensing analysis indicate that trees and agroforestry are already important components in the agricultural landscape of this region of the Indus-Ganges Basin. Diversifying agricultural production by including trees into the cropping system, either by the conversion of farming areas to agroforestry intercrop systems, or by planting bunds and boundaries, can lead to improved livelihoods, better economic security, and increased productivity for small farmers. Agroforestry systems do certainly have water use implications, but this study reveals that this may not significantly increase water use at the regional to basin scale, when these plantations are established on high-input, already intensively farmed irrigated areas.

Little difference in the annual vapor flow between agroforestry and crop systems is observed at the regional scale, even in scenarios of higher adoption levels. However, a pronounced spatial variation of vapor flow increase is observed as we move northward towards the Himalayan foothills, reflecting an increase in interception losses in the rainy areas of the region. Anecdotal impressions of farmers who irrigated agroforestry do not imply higher water consumption (Gupta et al. 2005) when compared to a typical crop system seem to be borne out by the results. Likewise, the impact on annual irrigation requirement for the region (even with widespread adoption of agroforestry) was minimal. The contribution of poplar to the local economy and farmer livelihoods is large and well established, yet this increase in trees within the irrigated agricultural landscape does not appear to translate to significantly higher regional water use. In particular, it has been found that the aggregated impact of trees planted on bunds and boundaries has little or no impact on regional water use, but can add significantly to farmer livelihoods and economic security.

The important biodiversity conservation aspects of growing trees outside of forests, for domestic and industrial uses, should not be underestimated. Most people agree on the desirability of conserving forest and wildlife habitat, but the growing demand for wood products continues to create increasing pressure on remaining forest reserves, especially in the tropics and developing countries. Growing economies and burgeoning populations in South

Asia, and the world generally, will continue to propel the need for these valuable renewable resources. Growing trees on-farm directly reduces pressure on forests, wildlife and biodiversity, while sequestering carbon from the atmosphere into wood and soils. Finding ways to meet the ever-growing demand for food, fiber, and shelter, on increasingly scarce and finite land resources must be aligned with the global intention to conserve biodiversity on this planet. One key to conserving forest ecosystems in tropical, densely populated developing countries like India lies in meeting its domestic wood demand from trees that are grown outside of forests, i.e., on-farm. In northern India, poplar production satisfies this demand for commercial softwoods, providing environmental services regionally through reduction of pressure on Himalayan forests, with only minimal predicted impacts on regional and local hydrological balances.

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