AGRICULTURAL INTENSIFICATION, SOIL FERTILITY DYNAMICS, AND LOW-COST DRIP IRRIGATION IN THE MIDDLE MOUNTAINS OF NEPAL

by

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ABSTRACT

The maintenance of soil fertility and access to water are essential to food production. This is of particular relevance to the subsistence-based farming systems of the Middle-Mountains of Nepal, which face tremendous pressure to feed a rapidly growing population. One means in which the demand for increased productivity is being met is through the intensification of agriculture. However, this has caused concerns over the long-term impacts on soil fertility. This study investigated if soil fertility has been compromised through agricultural intensification by comparing the soil status and inputs in intensively managed sites (sampled in 2000) to those of less-intensively managed sites (sampled in 1994). Nutrient budgets for nitrogen (N), phosphorus (P), and potassium (K) were developed to examine if inputs of these nutrients are sufficient to meet crop uptake.

Intensive farms utilize significantly more fertilizer and compost than less-intensive sites. The significant rise in fertilizer use has been accompanied by a shift in the use of predominantly urea to diammonium phosphate. This process has been driven by the introduction of potatoes and tomatoes into the cropping rotation and a decline in the use of a pre-monsoon fallow period. Phosphorus inputs to irrigated sites under intensive agriculture are considerably greater than crop uptake requirements, whereas inputs of N and K are insufficient, resulting in negative nutrient budgets. This imbalance has caused a significant increase in the level of available P in the soil and a significant decline in the level of amount of exchangeable K in the soil. In addition, intensification is accompanied by declines in the levels of base cations in the soil, which may indicate soil acidification. Farmers cultivating irrigated land need to address the serious deficits in exchangeable K, while reducing excess P inputs, and taking measures to reduce the potential of soil acidification. In contrast, intensive rainfed sites have large surpluses in N, P, and K budgets. Farmers could therefore reduce their inputs to minimize unnecessary economic expenditures and eutrophication of water sources, without risking a depletion of the soil nutrient pool.

Irrigation, as a source of water is the other means of increasing food production. Irrigation is particularly problematic in the rainfed lands of the Middle-Mountains due to topographical factors and water scarcity during the dry winter and pre-monsoon seasons. The performance of low-cost drip irrigation (LCDI), an affordable means of expanding irrigation into rainfed areas, was compared with conventional "Western" drip irrigation and hand watering for the cultivation of cauliflower. Comparisons were made between and among irrigation methods that were deficit irrigated and those that received full irrigation. Deficit irrigation refers to 50% of the estimated daily plant water requirement, whereas full irrigation refers to 100% of the estimated daily plant water requirement.

Western drip irrigation produced the lowest cauliflower yields, however differences in cauliflower yield between LCDI and hand-watered irrigation methods were inconclusive. There were no consistent differences in the soil volumetric water content between the three irrigation methods. Deficit irrigation resulted in lower soil volumetric water content and lower cumulative yields; however water-use efficiency was higher for deficit irrigation than for full irrigation. Overall yields were comparable to those observed in California and British Columbia. LCDI appears to be a better long-term strategy as less labour is required and because it results in greater profits once capital costs have been paid. In addition, under deficit irrigation, LCDI produced the greatest cauliflower yields implying that farmers in the water-scarce rainfed areas can viably cultivate an additional crop, increasing their economic and food security.

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1. INTRODUCTION

1.1. Research Context

Since the 1950's Nepal's population has more than tripled to over 23 million people in the year 2000 (FAO 2000a). This rapid growth has put significant pressure on Nepal's natural resources and raised concerns over the long-term sustainability of its agriculture. These concerns are particularly relevant in the Middle-Mountain region, which has historically been the most populated region and where the overwhelming majority of the population is dependent upon the land to fulfil their basic needs (Ministry of Population and Environment 2000). Crop yields from traditional hill farming systems are low and insufficient to feed the growing population (Pilbeam *et al.* 2000). Low yields have been attributed to poor soil fertility thus the maintenance of soil fertility has been identified as a serious concern in this region (Tuladhar 1994). Aggravating this problem, the strategies to increase food production, namely agricultural intensification and expansion into marginal lands, may further undermine soil fertility.

Traditional hill farming systems integrate forestry, livestock husbandry, and crop production and derive nutrient inputs primarily from manure sources. Agricultural intensification has meant an increase in the number of crops grown per year through the cultivation of crops with shorter-growing seasons. It has also resulted in a shift towards market-orientated production, with the cultivation of cash crops, particularly potato and tomato. The decline of fallow periods and the cultivation of more nutrient demanding crops requires greater nutrient inputs to maintain soil fertility. However, compost is a limited commodity as population growth places additional strain onto forests from which animal fodder and litter are collected. Farmers are increasingly relying on inorganic fertilizers, when available economically and temporally. With intensification of land-use, farmers perceive further declines in soil quality due to increased use of chemical fertilizers, soil acidification, and inadequate compost inputs (Turton *et al.* 1995).

Soil fertility is essential to land productivity. Equally important in food production is water for irrigation. Currently, approximately 70% of the cropped lands in Nepal are rainfed or *bari* (Land Resource Mapping Project (LRMP) 1986). Water supplies for bari lands are seasonal, in excess during the monsoon season and in deficit during the dry winter and pre-monsoon seasons. Lack of water often limits crop production to one, possibly two crops per year in rainfed plots. Furthermore, rainfed plots in developing countries commonly yield only half that of irrigated (*khet*) plots. Thus, access to irrigation is seen as one of the best ways to boost the productivity of small-scale dry-land farming systems (Postel 1999).

Drip irrigation, in which water is transported through pipes and applied in discrete amounts directly to the plant roots, is one of the most efficient means of watering crops. Drip irrigation can utilize water sources that are too small for use by other forms of irrigation. However, conventional drip irrigation systems are too expensive for the vast majority of hill farmers. The introduction of low-cost drip irrigation (LCDI) in Nepal presents the opportunity to rectify this situation and to substantially increase the economic and food security of many hill farmers. Access to irrigation provides farmers with the opportunity to grow an additional crop, to invest in higher yielding varieties, to maintain stable crop production, and to generate a cash income. In turn, income generation and food security allows farmers to conduct more integrated approaches to nutrient management, which is recognized as a means to maintain sustainable crop production (Sherchan *et al.* 1999).

This thesis focuses on two issues relevant to the Middle-Mountains of Nepal: soil fertility and irrigation. Concerns are often cited in the literature that agricultural intensification, triple-crop rotations, and shifts towards market-orientated production will result in inadequate compost inputs, increased reliance on chemical fertilizers, soil acidification, and further depletions of soil fertility (Tuladhar 1994, Turton *et al.* 1995, Carver 1997, Schreier *et al.* 1999, Schreier and Shah 1999, Bhattarai *et al.* 2001). However, a comprehensive examination of intensive farming systems and their effect on soils and inputs has not been undertaken in the Middle-Mountains. This thesis aims to provide a quantitative examination of the changes that occur in soil fertility with agricultural intensification.

The second component of this research relates to irrigation, specifically low-cost drip irrigation (LCDI). Farmers in the Tanahun district and in regions close to Pokhara have used LCDI successfully since 1996. LCDI is a relatively new technology to Nepal, and many hill farmers are unaware of its existence and its potential. At present, no studies have been undertaken in Nepal comparing the performance of LCDI with either western drip irrigation systems or hand-watering in terms of both crop yield and the soil volumetric water content.

The Jhikhu Khola watershed was chosen as the study area as it is typical of many Middle-Mountain watersheds in terms of climate, topography, soils, land use, and pressures on natural resources due to rapid population growth. Farmers in the region have intensified agricultural production and incorporated cash crops into their crop rotations in both khet and in bari lands. Water shortages have become of greater concern within irrigated lands as increased withdrawals have caused drops in the river levels, particularly during the dry season. The Jhikhu Khola is, however, "atypical" in that there is a high degree of road and market access. This makes it representative of future conditions that similar watersheds may experience as they become less isolated. In addition, the Jhikhu Khola watershed has been studied since 1989, providing a long-term data set on changing conditions.

1.2. Research goals

This thesis involves two components: an examination of soil fertility issues in intensively managed farming systems and a comparison of the performance of low cost drip irrigation systems with hand watering and a conventional drip irrigation system.

1.2.1. Soil fertility

Specific goals are to:

1. Examine the effect of agricultural intensification on soil fertility.

Research questions:

a) What is the current soil fertility status of khet and bari sites that have been intensively managed from 1995 to 2000?

b) How does the soil fertility of intensively managed sites compare to those less-intensively managed?

2. Examine the effect of agricultural intensification on the amounts and types of inputs used in farming systems

Research questions:

c) How have trends in compost and fertilizer use changed within intensively managed sites?

d) How do compost and fertilizer inputs compare between intensively managed and less-intensively managed sites?

e) Are current inputs to intensively managed sites sufficient to maintain positive budgets for nitrogen, phosphorus, and potassium?

f) How do nutrient budgets differ between intensively managed and less-intensively managed sites?

g) How do inputs relate to soil fertility?

1.2.2. Low-cost drip irrigation

Specific goals are:

1) to quantify and compare the operational parameters of each irrigation system: low cost drip irrigation, Western-drip, and hand-watered. Operational parameters assessed are the mean emission uniformity, mean flow rate, its variance, and the wetted area.

2) to quantify and compare the performance of each irrigation system and the effects of deficit irrigation and different irrigation scheduling. Performance will be evaluated using soil volumetric water content, the variability of soil volumetric water content, and biomass as indicators.

3) to develop a soil-water retention curve to relate measured soil volumetric water content to matric potential and thus plant stress.

4) to assess of the profitability of each irrigation method for a representative field size.

5) to determine water use efficiency of each irrigation method.

1.3. Thesis outline

Chapters 2 to 9 cover the soil fertility component of this research. These chapters will examine the current status of soil fertility of intensively managed sites, the nutrient flows within the agricultural system, the types and amounts of inputs, and the nutrient budgets of both intensive and less-intensive sites. In addition, the changes in soil fertility between less –intensive and intensive sites are examined.

Chapters 10 to 17 deal with the irrigation component of this thesis. These chapters provide an assessment of the operational parameters of the irrigation systems, the differences in soil volumetric water content both between irrigation methods and regimes. In addition, a comparison of the plant productivity, the economics, and the water-use efficiency of the systems will be presented.

2. STUDY AREA AND METHODOLOGY

An examination of soil fertility was conducted within the Jhikhu Khola Watershed as a whole, while the drip irrigation trial situated in Tamaghat at His Majesty's Government (HMG) Panchkhal Horticulture Farm.

2.1. Jhikhu Khola Watershed

2.1.1. Setting

The Jhikhu Khola watershed, which has an area of 111 km^2, is located approximately 40 km east of Kathmandu, in the Kabre Palanchowk District, within the Middle-Mountain region of Nepal (Figure 2.1). The valley floor, which is situated at ~ 800 m, is flanked on the north and south by steep slopes that rise up to 2030m intersected by boulder-bed confined tributaries and slopes greater than 30°. The Jhikhu Khola River runs along the main valley. The river is of alluvial origin and has slopes of 0.1° along its lower reaches.

The Jhikhu Khola had (in 1996) an estimated population of 48,728, a population density of 437 people/ km^2, and a population growth rate of 2.6 % per annum (Brown 1997, Allen *et al.* 1999). This makes it one of the most intensively used basins in the Middle-Mountains, a zone that traditionally has had the highest human occupancy and highest population growth rates in Nepal (Ministry of Population and Environment 2000). The Jhikhu Khola watershed is typical in that it shares many issues faced by other Middle-Mountain areas such as agricultural intensification, water shortages, soil fertility, soil erosion, and forest degradation, all problems associated with rapid population growth in a marginal environment (People and Resource Dynamics Project (PARDYP) 2000).

2.1.2. Land Use

The majority of inhabitants remain subsistence farmers relying on farming, livestock, and forest products, however a cash economy is gaining importance. An estimated 55 % of the watershed is under agricultural use: 17% as *khet* (irrigated) land and 38% as *bari* (rainfed) land. Forests comprise 30% of the land base and are important as sources of fodder and timber as well as a means of maintaining nutrient pools. Grassland and shrubland constitute 6% and 7% of the land respectively, while the remaining 3% of the watershed is classified as "other" (e.g. rocks) (PARDYP 2000).

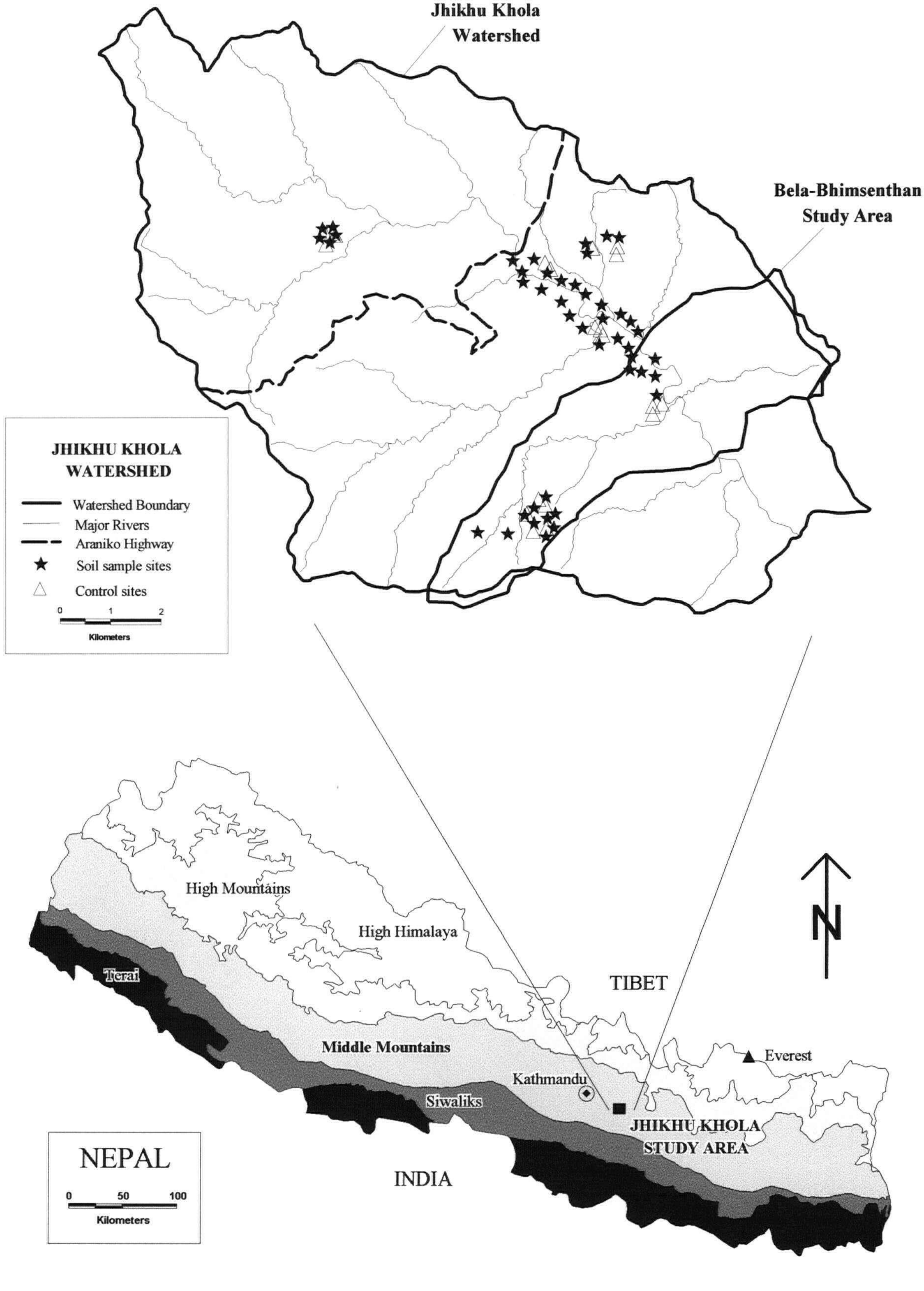


Figure 2.1. Location of the study area.

Khet land is dependent on irrigation water for at least 2 of 3 crops per year, with rice as the typical monsoon crop. Khet fields are typically bunded fields that are limited to the valley floor, tars and level terraces. Water is diverted from a stream or river, channelled through an elaborate network of irrigation ditches to a farmer's field and delivered via flood or furrow methods to the crop. Water user groups normally regulate irrigation. In contrast, *bari* lands are rainfed, typically upland sloping terraces in which maize or millet is the primary monsoon crop. Due to water limitations, traditionally only 2 crops per year are cultivated on bari lands (Tamrakar *et al.* 1991).

2.1.3. Soil types

Soils in the Jhikhu Khola can be broadly differentiated into red and non-red soils. Red soils are derived from deeply weathered quartzitic phyllittes. These are the oldest soils in Nepal and are highly susceptible to erosion and have poor physical properties. Red soils are dominated by Rhodustults and Haplustults (Brown 1997). Non-red soils are primarily Ustochrepts and Dystrochrepts formed on phyllite, schist, quartzite, sandstone and siltstone. Non-red soils are formed from quartzite and sandstone, characterized by a low cation exchange capacity and thus are susceptible to acidification and leaching (Schreier *et al.* 1995, Schreier *et al.* 1999).

2.1.4. Climate

As a result of variations in topography and aspect, the climatic regime within the Jhikhu Khola watershed ranges from a subtropical monsoon to a warm temperate climate. Seasons can be broadly delineated into a monsoon season (early June – late September), followed by a winter season (October-March) and a pre-monsoon season (April-May). Annual precipitation varies from 900 to 1600 mm. Up to 90% of this precipitation falls during the monsoon period. This is followed by a distinct dry period. In the Jhikhu Khola watershed, temperatures rarely fall below freezing during the cold periods, while in the summer temperatures may be in the high 30's (Carver 1997).

2.1.5. Market Access

The presence of two highways within the watershed makes the Jhikhu Khola watershed unique. The Arniko Highway intersects the Jhikhu Khola watershed and provides good access to Kathmandu and the Tibetan border, while the Sindhuli-bardibas Highway running along the upper southern flanks of the watershed will, upon its projected completion in 2003, provide additional access to Kathmandu as well as to south-eastern Nepal. This gives the Jhikhu Khola watershed a high degree of market access and infrastructure, and provides an ideal opportunity to document changes to natural resource systems with the introduction and establishment of a cash economy.

2.1.6. Long term data

The Jhikhu Khola watershed is a pertinent study location not only because it deals with both current and future problems of watersheds in the Middle-Mountains, but also because in 1989, a long term research project was initiated to examine issues in sustainable resource management. This project continues to run as a collaborative project between the University of British Columbia, the University of Bern, and the International Centre for Integrated Mountain Development (ICIMOD) in Kathmandu. Thus, topographic maps, air photos, documentation of climatic conditions, soil erosion, sediment transport, soil fertility, and socio-economic conditions exists allowing long term trends to be identified and providing a reference against which results of this thesis may be measured (Shah and Schreier 1995a).

2.2. Methodology

2.2.1. Field Methods: Soil Sampling

Soil samples were taken from intensively managed khet and bari sites and from control sites in 2000. A total of 65 samples were taken. Only non-red soils, defined as soils with hue values of 7.5 or 10 YR according to the Munsell colour chart, were sampled. At each site, 10 samples of 0-15 cm depth were collected and combined into one bulk sample. A 300g sub-sample was then taken and shipped to UBC for laboratory analysis. When possible, 5 bulk density and volumetric water content samples were taken from each site using a 3-cm high brass core. Soils were transferred into a moisture retention tin, weighed, placed in the muffle furnace in the PARDYP field office at 105 °C for a minimum of 24 hours, and subsequently reweighed to determine bulk density and volumetric water content. At all sites, soil samples were collected prior to the addition of any fertilizing material for the winter crop. Site locations were marked onto 1:5000 aerial photographs in the field and later georeferenced into a GIS database (Figure 2.1).

A farmer survey (Appendix 1) was conducted in 2000 at intensively managed sites to obtain information on crop yield, crop rotations, and additions of fertilizers, organic matter, and pesticides. In addition, farmers were asked to recall information on crop yield, crop rotations and inputs in 1995 for comparative purposes. Farmer surveys were not conducted in 1995, nor were soil samples collected. The accuracy of the 1995 dataset is equivalent to the accuracy of the farmers' memory. Overall trends are expected to be accurate, however, exact amounts of reported inputs and crop yields in 1995 should be interpreted with caution.

2.2.2. Khet sampling

'Intensive management' for khet sites was defined as land that had an annual crop rotation of greater than 2 crops per year including the cultivation of at least one nutrient demanding crop (e.g. tomato, potato) for four of the last 5 years. A total of 26 sites were sampled and surveyed along the Jhikhu Khola corridor from Panchkhal downstream to Baluwa on both sides of the river. Khet sampling was conducted between October 22nd and Nov. 21st, 2000, after the rice harvest and prior to the addition of fertilizer or organic matter to the subsequent winter crop.

2.2.3. Bari sampling

'Intensive management' for bari sites was also defined as having an annual crop rotation of greater than 2 crops per year for 4 of the last 5 years. However, as intensive management is an option for only the few farmers with sufficient access to water and resources, no requirements were placed on crop type. This was done to attain an adequate sample number. Ten samples were collected from Bela, 5 from Kubinde, and 5 from Rabi Obi. Sampling was conducted between September 16th and September 23rd, 2000, prior to the cultivation of a winter crop.

2.2.4. Control site sampling

Khet

Control sites were defined as lowland, grassy sites that have been uncultivated for a minimum of 10 years. Control sites in the khet areas were difficult to find due to the intensive nature of agriculture in which virtually all available land is cultivated. Eight grassy control sites were sampled. No survey was conducted for control sites, however local farmers verified the absence of cultivation at the sites. One control site was situated within the premises of HMG Tamaghat Horticultural farm; additional control sites were located in areas no longer suitable for agriculture due to bank undercutting by the river.

Bari

Control sites in bari areas were also defined as upland, grassy sites that have been uncultivated for a minimum of 10 years. Three control sites were sampled from Rabi Obi and Kubinde respectively. Five were sampled from Bela. In all three areas, control sites were situated in communal lands as well as in fields that were no longer cultivated.

2.2.5. Less-intensive sites

Soil parameters and input amounts for less-intensive sites represent a subset of data originally presented by Brown in 1997 collected from the Bela-Bhimsenthan study area in 1994. Only sites which were classified as non-red soils with a cropping rotation of ≤ 2 crops per year were included in the data set. As can be seen from Figure 2.1, the region in which less-intensive sites were sampled from represents only a portion of the total area sampled for intensive sites. However, they are representative of farms in the broader area prior to intensification and thus comparisons are justifiable (Brown, pers. comm. 2002). A total of 26 less-intensive khet sites and 32 less-intensive bari sites were included in the analysis.

2.2.6. Laboratory Methods

All soil samples were air dried, passed through a 2 mm sieve, bagged and shipped to the Pedology Laboratory at the University of British Columbia for analysis of % carbon and nitrogen, pH, available P, exchangeable cations (Ca, Mg, K, and Na), cation exchange capacity (CEC), and base saturation.

Percent carbon and nitrogen were determined through combustion of a 1.5 – 2.0 g sample in the Leco CN 2000 ™ induction furnace. An Orion™ pH meter was used to determine the pH of a 1:2 soil: 0.01 M $CaCl_2$ ratio. Available P, measured as orthophosphate, was determined using a Bray I solution and a Quik-Chem FIA+ Lachat autoanalyzer ™. Cation exchange capacity, exchangeable cations, and base saturation were obtained from a 10 g sub-sample run through an ammonium acetate extraction (pH 7.0) and a Quik-Chem FIA+ Lachat autoanalyzer ™ (University of British Columbia 1999).

3. INTRODUCTION: AGRICULTURAL INTENSIFICATION

In Nepal, with one of the highest population growth rates in Asia, the ability to produce additional food is a serious concern since access to agricultural land is finite and 80% of the population is dependent upon subsistence agriculture. Food production per capita is declining as recent yield increases of staple crops are generally attributed to the expansion of agricultural land rather than to production increases (Pandey *et al.* 1995, FAO 2000a). To meet the demand for increased food, agriculture has intensified and expanded onto marginal lands, causing concern over the long-term sustainability of agriculture. This section of the thesis will explore the issues relating to the intensification of agriculture.

Agricultural intensification is characterized by an increase in the number of crops grown per annum. Under intensive Nepalese farming the annual crop rotation is as high as 3-4 crops per year, a considerable increase from the national average of 1.3-1.6 crops per year reported by Hagen's (1980) and Panth and Gautam's (1987). Increases in cropping rotation have also been accompanied with a shift towards the cultivation of cash crops such as potato, tomato, and onion, many of which are more demanding of soil nutrients than staple cereal crops. The decline in the use of a fallow period and the cultivation of more nutrient demanding crops has raised fears that inputs (compost and/ or chemical fertilizer) are insufficient to meet increased crop uptake, thus further degrading soil fertility. Limitations in compost supplies have raised concerns that farmers are preferentially applying compost to intensive fields, in particular, shifting compost use from bari (rainfed) to khet (irrigated) fields and thereby stressing soil fertility in bari fields. Intensification is often associated with an increased dependence upon chemical fertilizers, and thus the potential acidification of soils with an inherently low pH, is an additional concern (Tuladhar 1994, Turton *et al.* 1995, Carver 1997, Schreier *et al.* 1999, Schreier and Shah 1999, Bhattarai *et al.* 2001).

The following chapters will examine these issues in the context of the Jhikhu Khola watershed. Chapter 4 will examine the status of soil fertility of intensively managed khet and bari sites, Chapter 5 will provide background into the factors that affect the management of nutrient flows within hill farming, and Chapter 6 will report on the amount and the nature of agricultural inputs to both intensively managed sites (triple crop rotation) sampled in 2000, and to less-intensive sites (double crop rotation) sampled in 1994. Chapter 7 will examine whether inputs are adequate for intensive and less-intensive farms using nutrient budgets, while Chapter 8 will examine whether intensification has caused changes in soil fertility.

4. SOIL FERTILITY IN THE MIDDLE-MOUNTAINS

A brief explanation to the factors related to the soil fertility of typical soils will be presented followed by an examination of the soil fertility status of soils from intensively managed sites surveyed in the Jhikhu Khola watershed.

Soils in the Middle-Mountains are typically characterized by low levels of pH, carbon (C), nitrogen (N), base cations, cation exchange capacity (CEC), and available phosphorus (P), but with abundant levels of exchangeable potassium (K). The low pH in Middle-Mountain soils is related to the dominance of quartz in the geologic formation and the leaching effect of heavy rainfalls. Relevant anthropogenic factors include the use of acid causing fertilizers, pine litter in compost, and the lack of lime within farming systems. Similarly, the low CEC is also related to the inherited bedrock conditions (extensive weathering results in kaolinite being the dominant clay mineral) and the low organic matter content in the soils (Schreier *et al.* 1995, Shah and Schreier 1995a, Schreier *et al.* 1999, Schreier and Shah 1999).

Phosphorus availability is affected by pH. Iron (Fe) and aluminium (Al) become increasingly soluble at low pH resulting in the formation of insoluble phosphates thus, in strongly acidic soils available P is typically low. Low levels of carbon and nitrogen within soils are related to the limited organic litter availability and the limited return of organic residues to fields. The prevalence of potassium (K) is linked to the wide distribution of mica within the parent material (Schreier *et al.* 1995, Shah and Schreier 1995a, Schreier *et al.* 1999, Schreier and Shah 1999).

4.1. Soil fertility status of intensive soils

With respect to soil fertility, intensively managed khet and bari sites are below desirable levels for crop production in terms of pH, CEC, carbon, nitrogen, magnesium, and for khet only, potassium. Calcium and base saturation are adequate while available P is high (Table 4.1).

Table 4.1 Soil fertility status (0-15 cm depth)

Variable (mean value)	Khet[a] (n=26)	Bari[a] (n=20)	Khet Control (n=8)	Bari Control (n=11)	1994 Khet[b] (n=26)	1994 Bari[b] (n=32)	Jhikhu Khola[c] (n=225)	Desirable Levels[e]
pH ($CaCl_2$)	5.0 (0.3)	4.9 (0.5)	5.2 (0.3)	4.8 (0.4)	5.0 (1.4)	4.8 (0.4)	4.6	5.0-6.5
CEC (cmol/kg)	9.4 (3.2)	8.55 (2.27)	9.6 (2.3)	8.4 (2.4)	9.9 (2.3)	8.4 (2.8)	10.4	>15
ex-Ca (cmol/kg)	4.28 (1.96)	3.29 (1.37)	4.35 (1.37)	3.10 (1.34)	4.98 (1.70)	3.36 (1.19)	2.58	>3.0
ex-Mg (cmol/kg)	0.98 (0.51)	1.13 (0.41)	1.35 (0.61)	0.96 (0.37)	1.13 (0.70)	1.17 (0.50)	0.99	>1.5
ex-K (cmol/kg)	0.13 (0.05)	0.40 (0.18)	0.32 (0.17)	0.18 (0.11)	0.20 (0.15)	0.25 (.20)	0.29	>0.25
Base saturation (%)	57.5 (12.5)	58.4 (15.0)	62.8 (9.7)	52.8 (16.6)	64. 7 (11.1)	58.5 (11.2)	39.0	>50
Carbon (%)	1.15 (0.34)	0.89 (0.36)	1.03 (.20)	0.88 (0.26)	0.90 (0.34)	0.98 (0.35)	1.01	1.5-2.0
Nitrogen (%)	0.10 (0.032)	0.08 (0.034)	0.08 (0.015)	0.06 (0.02)	-	-	-	>0.2
Available P Bray II (mg/kg)	99.1 (57.8)	100.3 (114.2)	6.0 (71.1)	8.2 (14.2)	20.8 (20.0)	16.5 (26.5)	2.1	>15
Available P Bray II (mg/kg)	339.5 (181.2)	151.3 (156.6)	16.3 (16.7)	16.6 (31.2)	-	-	-	-

Numbers in parenthesis represent one standard deviation

[a] Khet and Bari refers to intensive samples of each land-use within Jhikhu Khola.
[b] Data obtained from Brown (1997). All samples obtained from within Jhikhu Khola. Samples represent less-intensive (double-crop rotation) sites.
[c] Schreier *et al.* 2000
[e] Landon 1984, Miller and Donahue 1990

1994 khet and bari samples consist of non-red soils with a maximum crop rotation of 2 crops/ year sampled in the Bela-Bhimsenthan sub-watershed of the Jhikhu Khola. This is a sub-set of the data originally presented by Brown (1997). The Jhikhu Khola samples represent soil conditions for the entire watershed (khet, bari, forest and grassland). Desirable levels apply to crop production in tropical soils. The following discussion will focus on the soil fertility of intensive khet and bari samples. Comparisons of the soil fertility status of intensive samples to that of control sites and to less-intensive (2-crop) sites will be presented in Chapter 6.

Soil pH is a measure of the acidity or basicity of a soil. It is an important factor in controlling the solubility and precipitation of essential elements and thus, their relative availability to plants. The mean pH for both khet and bari soils may be classified as strongly acidic (Brady 1990) with 54% and 60% of soils below a pH of 5.0 for khet and bari. Below a pH of 5.5, P, Ca, Mg, boron (B) and molybdenum (Mo) begin to become deficient, and manganese (Mn), Fe, and Al increase in solubility, becoming increasingly toxic to plants (Prasad and Power 1997).

The buffer capacity of a soil is related to its cation exchange capacity (CEC) and to the amount of organic matter present. CEC is influenced by clay content, clay mineralogy, and organic matter. This latter factor is particularly important in heavily weathered tropical soils. In addition, CEC is pH-dependent due to Al and Fe hydroxides (Sanchez 1976, Prasad and Power 1997). The low pH, the low organic matter content, and the kaolinite-dominated clay content of the soils all contribute to the low mean CEC of both khet (9.4) and bari (8.6) soils. Ninety-two percent of khet and 100% of bari samples have CEC levels lower than desirable levels for crop production (15 cmol/kg). As CEC represents the reservoir of base cations the soil can hold, low CEC values have negative implications on the amount of essential plant nutrients the soil can retain and on its buffering ability to acidic inputs, such as fertilizers (Sanchez 1976, Prasad and Power 1997).

Base saturation represents the proportion of cation exchange sites occupied by exchangeable base cations (K, Mg, Na, Ca) that are available for plant uptake. Base saturation is inversely related to soil acidity. Thirty percent of both khet and bari samples were below desirable levels of base saturation (50%), although the mean of the samples was adequate.

Levels of exchangeable cations indicate not only the existing nutrient status, but also the balance among cations influencing both soil structure and nutrient uptake by crops. Calcium availability will be affected by relative amounts of magnesium and potassium. Calcium deficiencies, as a plant nutrient, do occur in soils with low CEC at pH values ≤ 5.5. In addition, high Mg:Ca ratios will limit Ca availability and weaken soil structure though increased clay deflocculation. In contrast, magnesium becomes progressively less available for plants as Ca:Mg ratios become greater than 5:1. Ratios between 3:1 and 4:1 are considered optimal for most crops. Similarly, excess K^+ antagonizes Mg uptake, with uptake becoming increasingly limited as the K:Mg ratio becomes greater than 2:1 (Landon 1984, Prasad and Power 1997).

Exchangeable Ca levels are adequate (>3 cmol/kg) in both khet and bari soil samples. In contrast, levels of exchangeable Mg are below desirable levels (1.5 cmol/kg). The mean Ca:Mg ratio for khet samples is 4.6, within the optimum range for most crops, although 35 % had ratios of > 5.1 suggesting Mg uptake may be inhibited for these sites. Fifty-five percent of bari sites had Ca:Mg ratios < 3:1, indicating P uptake may be inhibited (Landon 1984). The mean Ca:Mg ratio was 3.0. All K:Mg levels are less than 2:1, indicating that, for both khet and bari, calcium and magnesium uptake is not being inhibited by excess potassium.

Potassium fixation is related to clay content (e.g. kaolinites fix small amounts of potassium) and is inversely related to soil pH (for pH <6.0). Little potassium exists in the organic form as potassium within organic matter is rapidly leached out and dissolved into soil solution where it may then react with clay minerals. Desirable absolute levels of K are >0.25 cmol/kg, while the minimum relative levels of the sum of all exchangeable bases (K:CEC) is 2%. All khet samples have less than desirable levels of absolute and relative K. Bari sites have adequate levels of K, with 70% of bari sites possessing absolute K levels above desirable levels and a mean relative K of 4.8%. The low levels of potassium within khet soils represent a divergence from conditions normal to the Middle-Mountains, where potassium is typically adequate.

Soil organic matter (SOM) plays a disproportionately important role in a soils' physical and chemical properties considering it only comprises up to 5%, on a weight basis, of mineral soils. Maintaining SOM is important to retain reasonable levels of CEC in highly weathered tropical soils. Percent carbon is directly proportional to SOM and influences the level of percent nitrogen. The C:N ratio provides an indication of the rate of organic decay, the type of organic matter and available nitrogen levels, with a ratio slightly lower than 10:1 considered an equilibrium value for the tropics. Straw residues will increase C:N ratios while legume residues will decrease the ratio (Landon 1984, Brady 1990, Prasad and Powers 1997).

Percent carbon and nitrogen content for all khet and bari samples is low. Furthermore, 70 % of bari and 38 % of khet samples have "very low" levels of percent nitrogen (< 0.1%). Mean C:N ratios are 11.0 for khet and 11.5 for bari indicating that organic residues may be slightly higher in straw residues.

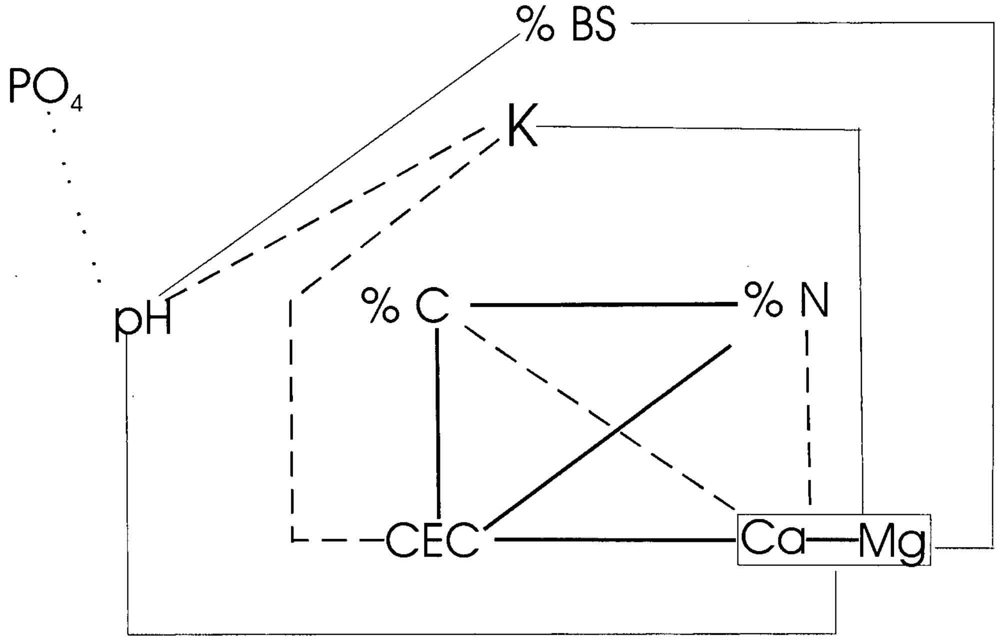
Phosphorus (P), which after nitrogen is the most critical essential element influencing plant production, is typically a limiting nutrient within the Middle-Hill farming systems. Khet and bari samples did not exhibit the expected low levels of available P. Both land use types have high levels of available P (99.6 mg/kg and 100.3 mg/kg respectively). (A minimum desirable level for available P is 15 mg/kg.) Only one khet site and one bari site sampled had available P levels below 15 mg/kg. (Sanchez 1976, Schreier *et al.* 1999).

Micronutrient deficiencies will also limit plant growth and affect crop yield. Sherchan *et al.* (1991) identified that in high intensive cropping areas micronutrient deficiencies, especially boron and molybdenum, were of concern, while Gupta *et al.* (1989) reported boron, magnesium, copper, calcium, and zinc deficiencies in mandarin growing areas. Sherchan and Gurung (1995) report that cabbage and cauliflower crops in areas with off-season vegetable cultivation show signs of boron and molybdenum deficiencies. Although micronutrients were not analysed in this study, it is hoped that future work may examine the effects of intensification and potentially imbalanced fertilizer applications on micronutrient availability.

4.2. Soil variable correlations

Relationships between soil parameters were calculated for variable pairs using Spearman's rho correlation coefficients. Variables with a r^2 value greater than 0.3 (95% confidence interval) are illustrated in Figure 4.1 and Figure 4.2.

4.2.1. Khet



_ _ _ represents $0.3 \geq r^2 > 0.4$ ______ represents $r^2 > 0.6$
______ represents $0.4 \geq r^2 > 0.6$ . . . . represents negative $0.4 \geq r^2 > 0.6$

Figure 4.1 Correlations between soil variables in intensive khet sites (n=26, Spearman's rho)

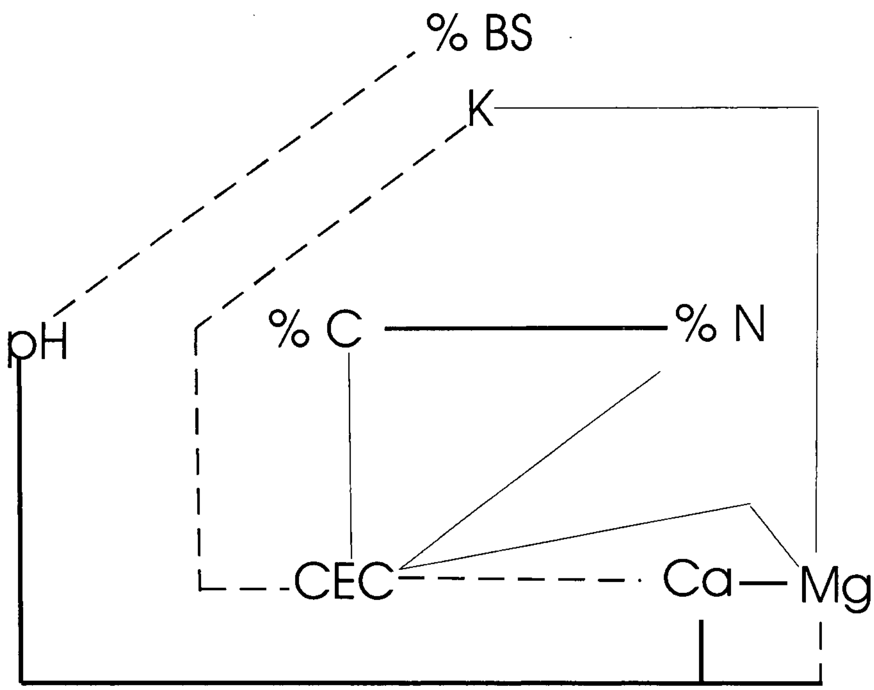
In intensive khet samples, strong positive correlations exist between Ca and Mg and between % C and % N. In addition, strong positive correlations exist between cation exchange capacity and % C, % N, exchangeable Ca, and exchangeable Mg (Figure 4.1).

The positive relationship between CEC and soil organic matter (represented by % C and % N) that was observed (Figure 4.1) is expected since in highly weathered tropical soils, a significant amount of the total exchange capacity is derived from organic matter. The positive correlation between Ca and Mg (the dominant exchangeable bases within soils) and CEC that was present was also expected as with an increase in the soil's total ability to hold onto cations an increase in the relative amounts of Ca and Mg is to be expected.

Moderately positive relationships exist between base saturation and pH, between base saturation and Ca – Mg, and between potassium and Ca – Mg (Figure 4.1). The positive correlation between base saturation, pH and Ca and Mg is due to the replacement series of cations (the ease of replacement is such that $H^+ > Ca^{2+} > Mg^{2+} > K^+ > Na^+$) and the Law of Mass Action. At low pH, exchange sites are predominantly occupied by H^+, but as pH increases, the concentration of Ca and Mg increases and they occupy proportionately greater numbers of exchange sites. The positive correlation between K and Ca and Mg reflects that with increasingly basic conditions a greater abundance of all cations exists.

A moderate negative correlation between pH and available P also exists. This is opposite to the expected result in which available P increases with increasing pH due to the reduction in the formation of insoluble Fe and Al phosphates. This was an unexpected result and may be related to management factors (e.g. soils with an inherently higher pH are considered more fertile, thus farmers with these soils apply less fertilizers, the primary reason for high levels of available P).

4.2.2. Bari



_ _ _ represents $0.3 \geq r^2 > 0.4$ ______ represents $r^2 > 0.6$

______ represents $0.4 \geq r^2 > 0.6$

Figure 4.2 Soil correlations in intensive bari sites (n=20, Spearman's rho)

In bari samples, strong positive correlations exist between % C and % N and between pH and Ca (Figure 4.2). The strong positive correlation between pH and Ca is again linked to the replacement series of cations and the Law of Mass Action. Unlike khet samples, the positive relationship between CEC and % C, % N was only moderate and only weak for Ca and Mg, however the same theoretical principles apply.

In addition, in bari soils no correlations exist between potassium and calcium and between potassium and magnesium and between pH and Mg (Figure 4.2) as in khet samples.

The strong positive correlation between C and N exhibited in both khet and bari is expected as C is directly proportional to SOM and an increase in SOM will be associated with an increase in percent N. In addition, the C:N ratio in soils is typically fairly constant supporting the observed correlation. Similarly, the strong positive correlation observed between Ca and Mg is also expected since these ions have the same charge, similar ionic radius, and act in a similar manner within soil, and thus if one is present so is the other. A positive correlation between pH and available P was found in previous studies, however, these studies included red and non-red soils. Increasing the sample size and/ or including red soils would strengthen the power of these results.

4.3. Summary: Soil fertility status

With respect to soil fertility, intensively-managed khet and bari sites are below desirable levels for pH, CEC, carbon, nitrogen, magnesium, and for khet only, potassium. Calcium and base saturation are adequate while available P is high. Strong positive correlations exist between carbon and nitrogen and between Ca and pH in both khet and bari.

The high levels of available P in intensive khet and bari soils and the low levels of potassium in intensive khet soils differ from the expected soil fertility status of adequate levels of potassium and low levels of available P typical of previous studies in the Middle-Mountains.

5. NUTRIENT FLOWS

Nutrient flows in to and out of agricultural systems ultimately determine soil fertility. An understanding of how various physical and social factors influence both the quantity and the quality of nutrient flows can provide insights into the management of soil fertility. Compost, fertilizers, irrigation, sediment redistribution, atmospheric sources, and biological fixation all provide nutrients to the soil. In contrast, crop harvest, soil erosion, leaching, gaseous losses and chemical fixation represent nutrient losses from the soil systems at a variety of time-scales. Maintaining nutrient flows such that withdrawals from the soil nutrient pool do not exceed inputs will ensure that the soil pool is not mined. The social and physical factors that will be discussed in the subsequent sections, in terms of their impact on nutrient flows and soil fertility within the Middle-Mountains and the Jhikhu Khola watershed are illustrated in Figure 5.1. Linkages between the soil status and nutrient flows will be further examined in Chapter 7 and Chapter 8.

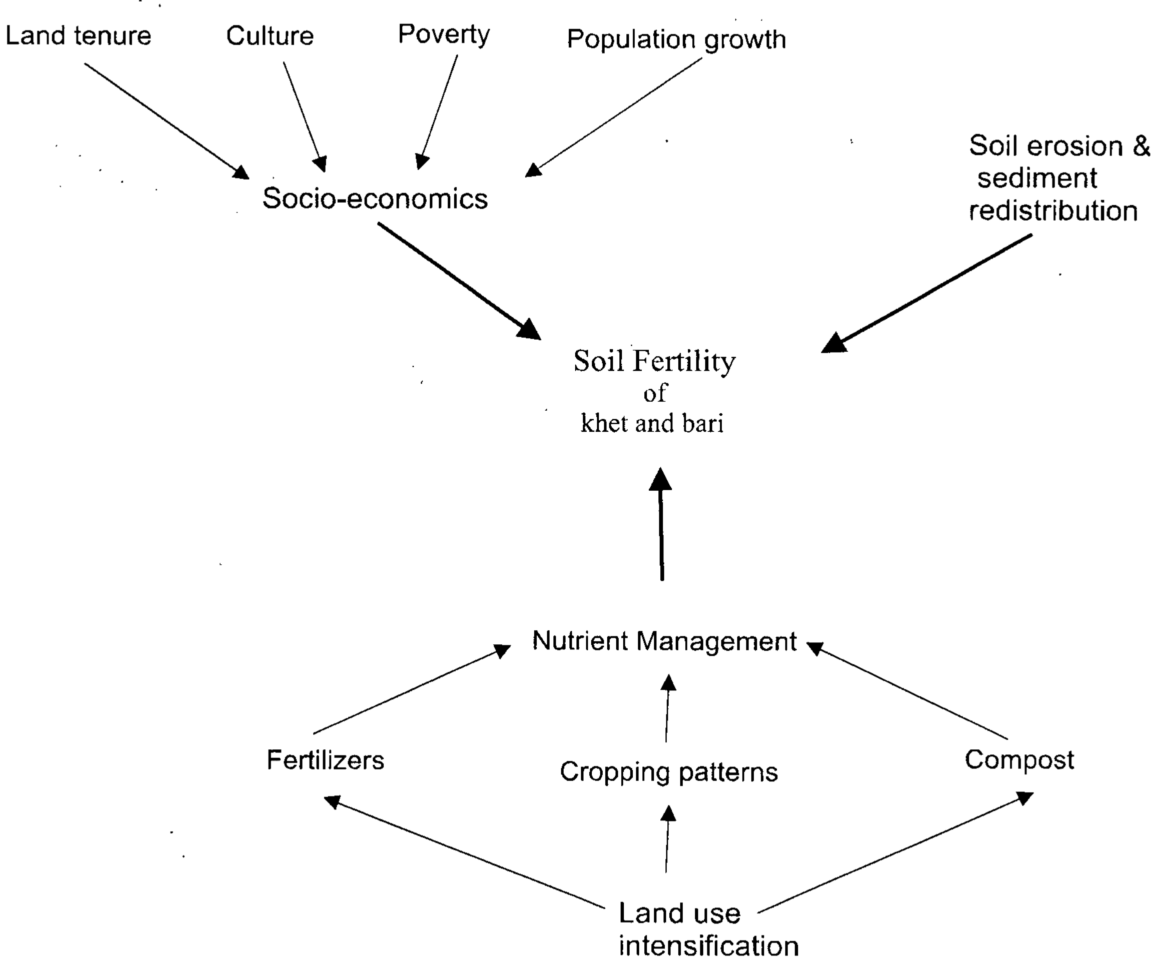


Figure 5.1 Factors affecting nutrient flows and soil fertility.

5.1. Nutrient Management

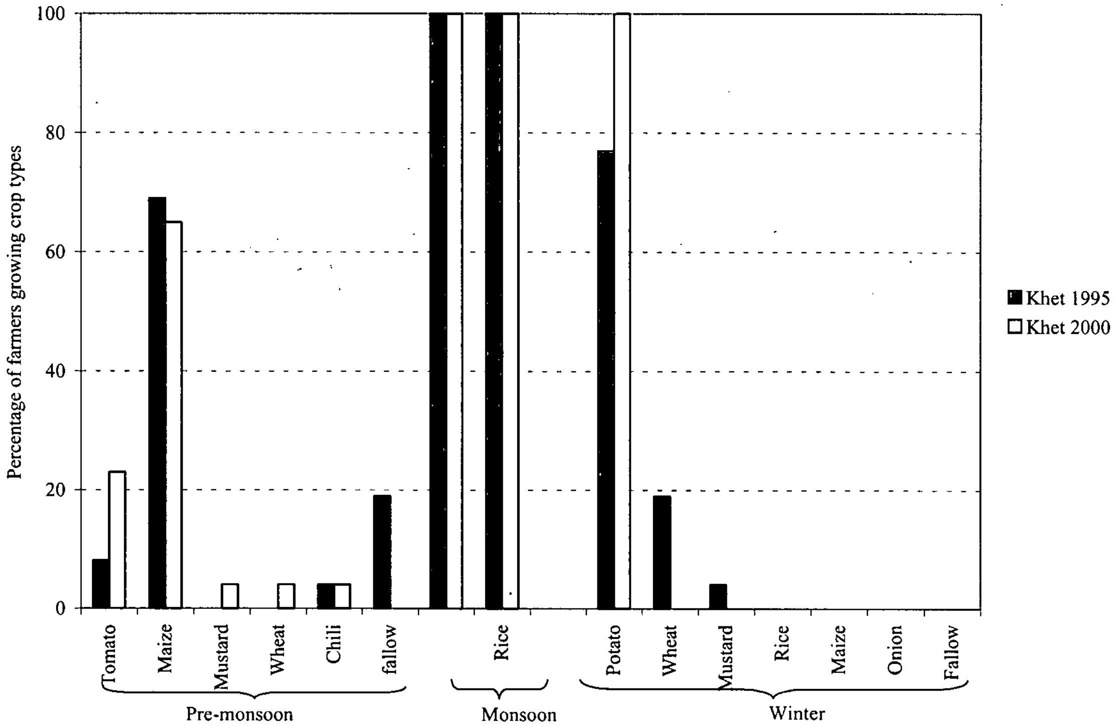
Nutrient management encompasses the management of soil nutrient flows at a farm level. This is controlled by the cropping pattern, the amount of crops grown per annum, the quality and quantity of compost applied, and the type and amounts of fertilizers applied. Intensification will affect each of the above factors thereby altering nutrient flows.

5.1.1. Cropping Patterns

In the Middle-Mountains of Nepal the predominant cropping pattern for khet is a rice-based double crop rotation, typically a monsoon rice crop, followed by a winter wheat crop and then a pre-monsoon fallow period. In bari, it is maize-based rotation, typically a maize-millet-fallow rotation or, in the case of the Jhikhu Khola Watershed, a maize-wheat-fallow rotation. Rice, maize, and wheat, are considered staple crops within the Jhikhu Khola Watershed, while potato, tomato, onion, garlic, and cauliflower are cash crops. (Sthapit *et al.* 1988, Brown 1997, Pilbeam *et al.* 1999, Sherchan *et al.* 1999)

Figure 5.2a compares crops grown in 1995 and in 2000 as reported by farmers for intensively managed khet sites. In both 1995 and 2000, the monsoon crop for all intensively managed khet sites is rice. However, changes in the cropping pattern between 1995 and 2000 are present in both the winter and pre-monsoon season. Although the majority of intensively managed khet sites (77%) reported that potato was grown during the 1995 winter season, 19% reported the cultivation of wheat. However, by 2000 all intensively managed khet sites surveyed cultivated potato. In the pre-monsoon season, there is a 15% increase in the number of farmers cultivating tomato between 1995 and 2000. In 1995, 19% of intensively managed khet sites incorporated a fallow during the pre-monsoon season. This declined to zero by 2000 (Table 5.1). The cropping pattern of less-intensive khet sites that were sampled in 1994 is a predominantly a rice-wheat- fallow rotation (Figure 5.2b). A direct temporal comparison cannot be made between the cropping pattern sampled in 1994 and that reported by farmers in 1995 as the sites are spatially different and due to the sampling scheme, which was designed to compare intensive with less-intensive managed sites rather than conditions of sites in 1994 and 2000. In the winter season, intensification has been accompanied by increases in the cultivation of potato and declines in the cultivation of wheat. In the pre-monsoon season, the trend as farmers intensify is a decline in the use of a fallow and increases in the cultivation of maize and tomato crops.

a)



b)

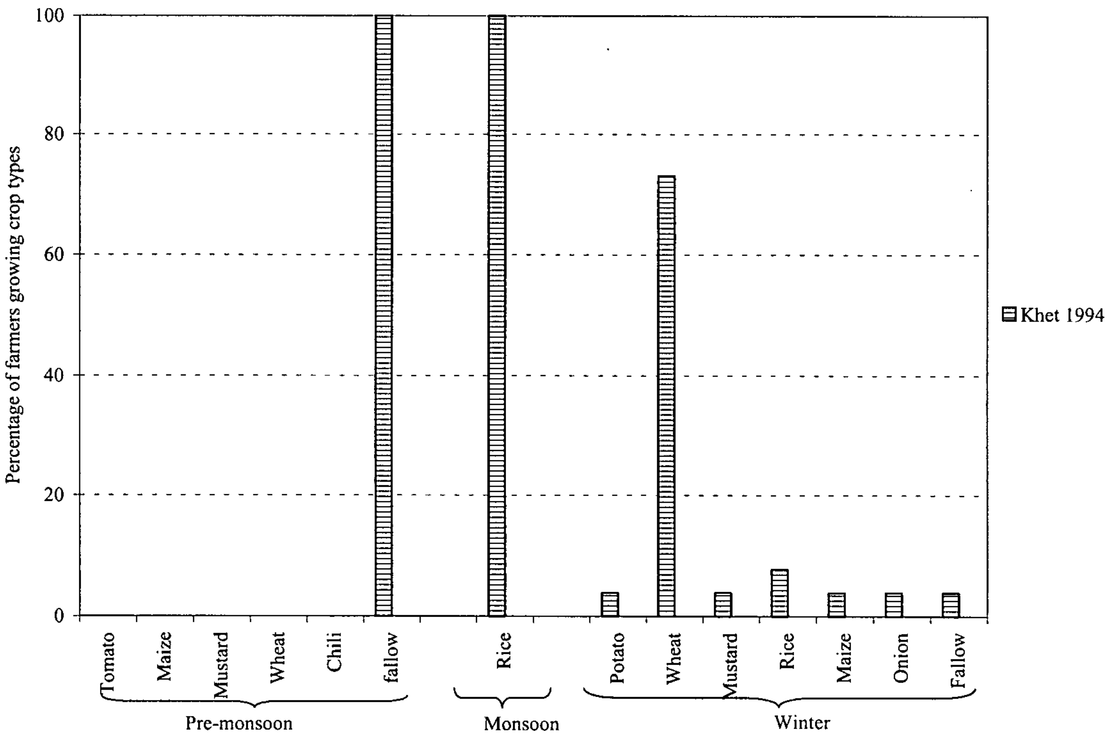
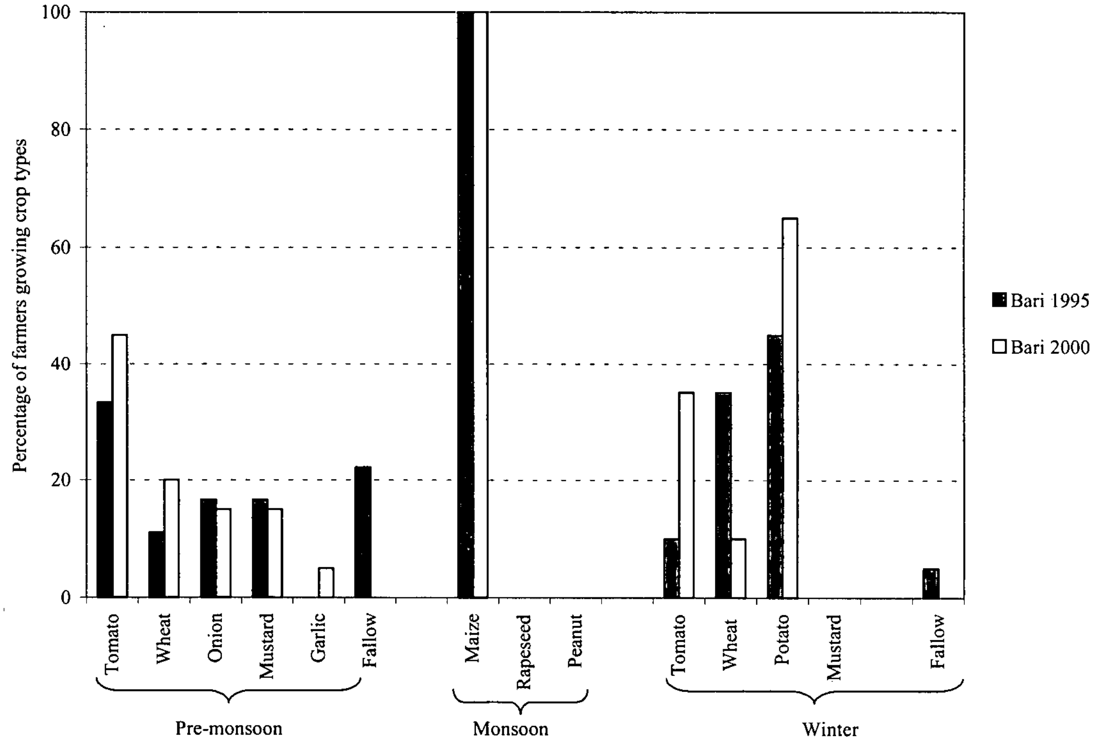


Figure 5.2 Cropping pattern in a) intensively managed khet sites in 1995 and 2000 and b) less-intensively managed khet sites sampled in 1994.

a)



b)

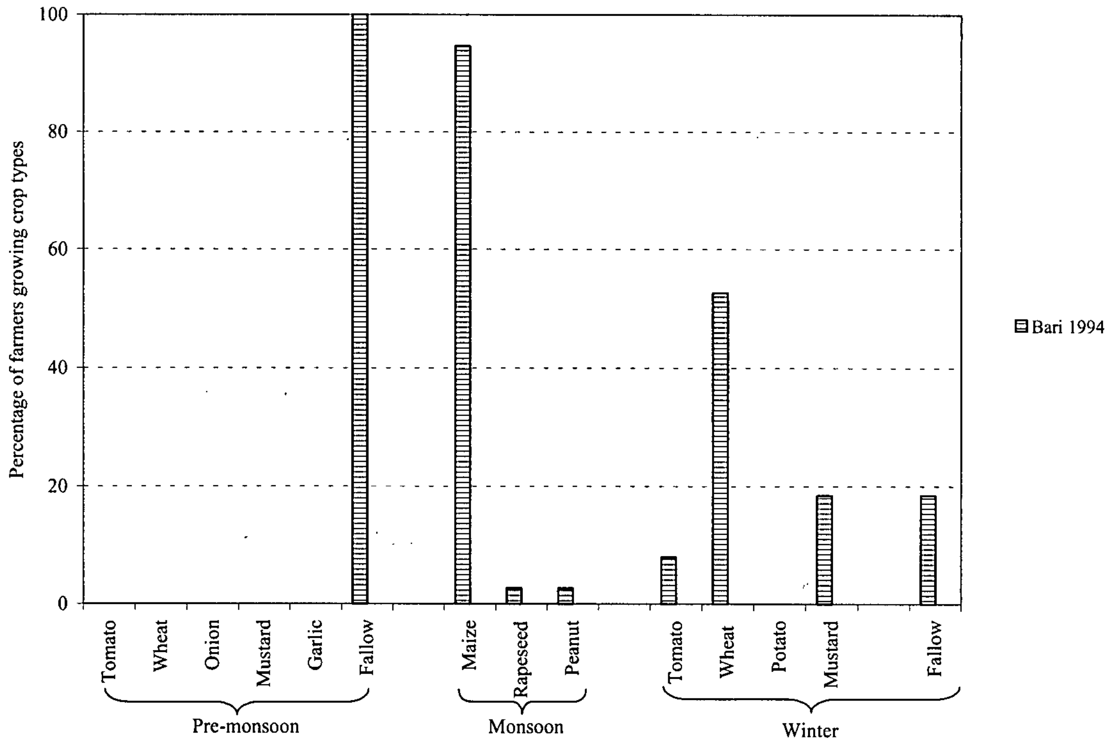


Figure 5.3 Cropping pattern in a) intensively managed bari sites in 1995 and 2000 and b) less-intensively managed bari sites sampled in 1994.

The availability of water in some bari areas has allowed farmers to cultivate 3 crops per annum, predominantly a maize-potato-tomato rotation in 2000 (Figure 5.3a). Similar to khet the crop cultivated during the monsoon season (maize) does not change between 1995 and 2000. In contrast, during the winter season a 19 % decline in the number of farmers growing wheat and an 11% decline for mustard occurs with a concomitant 18% rise in the number of farmers growing tomato and 12% rise for potato (Table 5.1). The predominant cropping pattern of less-intensive bari sites sampled in 1994 was a maize-wheat-fallow rotation. The trend in cropping patterns as bari farms move from less-intensive to intensive management is again manifested in the winter and the pre-monsoon crops, with a shift towards potato and tomato, both of which are cash crops and more nutrient demanding crops than wheat or mustard, as well as a decline in the use of fallow.

Table 5.1 Comparison of changes in cropping patterns between 1995 and 2000 within intensive sites.

Percent change in cropping pattern between 1995 and 2000						
	Pre-monsoon		Monsoon		Winter	
	Maize	- 4 %			Potato	+ 23 %
Khet	Tomato	+ 15%	Rice	0 %	Wheat	- 19 %
	Fallow	- 19%			Mustard	- 4 %
					Potato	+ 12 %
	Tomato	+ 12 %			Tomato	+ 18 %
Bari	Wheat	+ 9 %	Maize	0 %	Wheat	- 19 %
	Fallow	- 22%			Mustard	- 11 %

Eliminating fallow periods and cultivating more nutrient demanding crops, such as potato, (Tandon and Sekhon 1988) results in greater uptake of soil nutrients by crops. Thus, management of compost and fertilizer inputs becomes of greater importance to ensure that soil nutrient reserves are not depleted to levels detrimental to crop yield.

5.1.2. Crop Yield

Crops influence nutrient flows not only by the cropping intensity but also through yields. The larger the crop yield, the greater the uptake of soil nutrients, and thus the larger the flow of nutrients out of the system will be when crops are harvested. Crop species differ in both the amount and kind of nutrients they demand, for example potatoes have high N and K uptake. In addition, high yielding varieties typically have higher nutrient demands than local varieties. Crop yields typically also vary with location in response to differing environmental conditions or to the incidence of diseases and pests. (Pilbeam *et al.*1999). Mean yields for khet and bari are presented in Table 5.2, in conjunction with national and regional yield data. Note that regional yields represent both mean and/or the range of values and are not year specific in contrast to reported and national yields. Yield data from 1994 represents less-intensive sites with ≤ 2 crops per year, whereas yield data from 1995 and 2000 represents reported yield data from intensive sites with ≥ 3 crops per year.

Table 5.2 Reported crop yields, national crop yields and regional crop yields.

Land-type	Crop (Season)	Year	N	Reported yield (kg/ha) Mean ± std.dev.	National mean yield[a] (kg/ha)	Regional mean yield (kg/ha) [range]
Khet	Rice	2000 1995 1994	26 26 26	5786 ± 1252 5223 ±1797 3222 ± 1046	2600 2391 2124	3630[b] [1179-5050][c]
Khet	Potato (Winter)	2000 1995	26 19	23993 ± 6667 22660 ± 11219	9854 8593	
Bari	Potato (Winter)	2000 1995	13 9	10368 ± 6866 9447 ± 7094		
Khet	Maize (Pre-monsoon)	2000 1995	18 16	3236 ± 1396 2540 ± 485		1560[d]
Bari	Maize (Monsoon)	2000 1995 1994	20 18 32	3943 ± 1755 3850 ± 2068 4171 ± 1875	1701 1645 1650	2600[e] 2630[f] 3600[g]
Khet	Tomato (Pre-monsoon)	2000 1995	5 2	18949 ± 10563 6919 ± 890		
Bari	Tomato (Pre-monsoon)	2000 1995 1994	9 6 2	12449 ± 6625 14513 ± 7459 2231 ± 3156		
Bari	Tomato (Winter)	2000	5	5252 ± 2153		
Khet	Wheat (Winter)	1995 1994	6 19	2062 ± 683 1494 ± 1046	1550 1470	2310[d] [2000-3000][h]
Bari	Wheat (Pre-monsoon)	2000	4	1204 ± 164		
Bari	Wheat (Winter)	1995 1994	7 14	1987 ± 1350 1147 ± 624		[1675-5984][b]

[a] FAO 2000a
[b] Subedi *et al.* 1995
[c] Sherchan *et al.* 1999
[d] Subedi and Gurung 1991: represents average national yield for 1981/1982.
[e] Vaidya and Gurung 1995
[f] Tripathi 1997
[g] Subedi and Dhital 1997
[h] Subedi 1994

References [b-h] represent average yields obtained from experimental plots associated with the agriculture research station at Lumle or Pakhribas. Reported rice yields in 1994, 1995, and 2000 are greater than mean national averages in the respective years. Mean yields in 1994 are similar to those determined by Subedi *et al.* (1995) in a 2 year experimental trial. Mean yields reported in 1995 and 2000 are similar to the maximum yields determined by Sherchan *et al.* in 1991. Rice yields of intensive sites (as represented by the 1995 and 2000 dataset) are significantly greater than less-intensive sites (as represented by the 1994 dataset) (Table 5.2).

Potato yields for intensive bari were similar to the national average, whereas khet potato yields were significantly higher than both the national average yields and the bari yields. Maize yields, which range from a minimum mean of 2540 kg/ha for khet in 1995 (intensive) to a maximum mean of 4171 kg/ha for bari in 1994 (less-intensive), are greater than the national average but comparable to values noted by Subedi and Dhital (1997) and Tripathi (1997) in experimental trials. Mean maize yields in 1994 (less-intensive) are greater than intensive bari yields in both 1995 and 2000 (intensive) (Table 5.2).

Tomato yields vary considerably. The maximum median yield (18.9 t/ha) was determined for khet (pre-monsoon 2000), while the minimum median yield (2.2 t/ha) was for bari 1994. The median khet pre-monsoon tomato yield was 18.9 t/ha. This is comparable to the Indian national average yield (15 t/ha) in 2000 (FAO 2000a). Reported bari tomato yields appear to be low. Wheat yields are comparable to national averages and to values reported by literature sources (Table 5.2). Overall mean reported crop yields for sites within the Jhikhu Khola are greater than the national average. Yields are within the range determined in experimental plots for crops for which data exists.

5.1.3. Compost

Compost is an important supply of macro- and micronutrients; it contributes to the improvement of soil physical and chemical properties, and is important in the maintenance of soil biological communities (Bhattarai *et al.* 2001). In the Middle-Mountains compost has traditionally been the main source of crop nutrients, although other means of maintaining soil fertility are practiced (e.g. green-manuring, short fallow periods, slicing/burning of terrace risers, trapping of flood waters, inter-cropping with legumes, recycling of forest litters, and in-situ manuring). Compost may be a mixture of manure, organic residues, household wastes and ashes from cooking fires.

The low nutrient content of compost is related to its preparation and application methods. Farmers heap manure and organic matter into piles that are typically exposed to the elements with subsequent loss of nutrients through volatilization, leaching, and denitrification. Furthermore, many farmers partially dry compost before carrying it to the fields to lighten the load carried. Compost, often only partially decomposed, is then left in several smaller piles for up to 2-3 weeks before it is incorporated into the soil. This results in further nutrient losses (Sthapit *et al.* 1988, Subedi and Gurung 1991, Pandey *et al.* 1995, Bhattarai *et al.*2001). In addition, the composition of compost is becoming increasingly acidic due to the incorporation of chir pine (*Pinus roxburghii*) needles (Schreier *et al.* 1995).

In the Kavre district, manure improvement campaigns have resulted in a considerable increase in the number of farmers providing some form of protection (thatch, plastic cover, or tree shade) from the elements for compost (Jaishy 2000). Personal observations within the Jhikhu Khola valley suggest that the long "in-field" time before soil incorporation may be reduced by increased cropping intensity, due to reduced turn-around time between crops.

5.1.4. Nutrient content of compost

Values of the nutrient content of compost utilized by the farmers surveyed were not obtained thus values from local studies were used. An average value was taken of the nutrient content determined in traditional compost measured by the Lumle Agriculture Research Centre and that measured in six compost samples in the Jhikhu Khola in 2000. Values of % N (1.27), %P_2O_5 (0.31) and % K_2O (1.38) fall within the range measured by the Sustainable Soil Management Programme (SSMP 2001) for samples across the Middle-Mountains (Table 5.3).

Table 5.3 Nutrient content of compost

Location	% N	% P_2O_5	% K_2O	Reference:
Average: Jhikhu Khola + Lumle surveys	1.27	0.31	1.38	
Lumle	0.6	0.06	0.6	Suwal *et al.* 1991
Jhikhu Khola	1.93 ± 0.41 (n=6)	0.56 ± 0.13 (n=6)	2.15 ± 0.27 (n=6)	Brown, pers. comm. 2001.
Middle-Mountains Mean:	0.83 (n=460)	0.70 (n =42)	2.26 (n=42)	SSMP 2001
Range:	0.1 - 2.47	0.22 - 1.41	1.31 – 3.96	
Kavre district Mean:	1.38 (n=4)	1.51 (n=4)	2.98 (n=4)	Bhattarai *et al.* 2001
Range:	1.00 - 1.97	0.96 - 2.10	2.67 – 3.24	

Prior to transport the moisture content of the compost pile is 40-60%, while the on-field moisture content is approximately 25 % (P.B. Shah, pers. comm. 2001, SSMP 2001). A value of 25 % moisture content was used for all calculations

5.1.5. Compost Use

Farmers determine the amount of compost to apply to their fields based on the crops being grown, the distance between the house and their fields, the availability of organic matter, labour, and chemical fertilizer, and on the soil fertility status. Subedi and Gurung (1991) reported application rates of 20-28 t/ha with a maximum of 58 t/ha for a maize/millet rotation, while khet rice rotations received 0-23 t/ha. Tuladhar (1995) reported application rates of 20-50 t/ha for bari land. Gurung and Neupane (1991) cite values of 18 t/ha for bari and 11 t/ha for khet. Brown (1997) recorded a maximum of 98t/ha of compost with average bari values of 12 t/ha and khet values of 4 t/ha.

Farmers report that the amount of compost available per unit land has declined due to land-use intensification, deforestation, and fodder shortages, and labour constraints (Sthapit *et al.* 1988, Bhattarai *et al.* 2001). Furthermore, organic matter traditionally applied to bari fields is being diverted to intensively managed khet sites (Brown 1997).

5.1.6. Compost use: Intensive khet

Compost additions in khet are seasonal (Figure 5.4a). Median application of compost, in both 2000 and 1995, was greatest for winter potato crops and least for pre-monsoon crops (Figure 5.4b). The maximum annual application rate in 2000 was 29 t/ha, with a median of 14 t/ha. This median value of 14 t/ha is within the range reported by various authors for the Middle-Mountains (e.g. Gurung and Neupane 1991 report a median application rate of 11 t/ha). In contrast, Brown (1997) reported a median value of only 4 t/ha for khet sites within the Jhikhu Khola. The increased median value reported in this study reflects the effect of the introduction of potato into the crop rotation, as few khet farms sampled by Brown cultivated potato, to which the majority of compost is applied (Table 5.4).

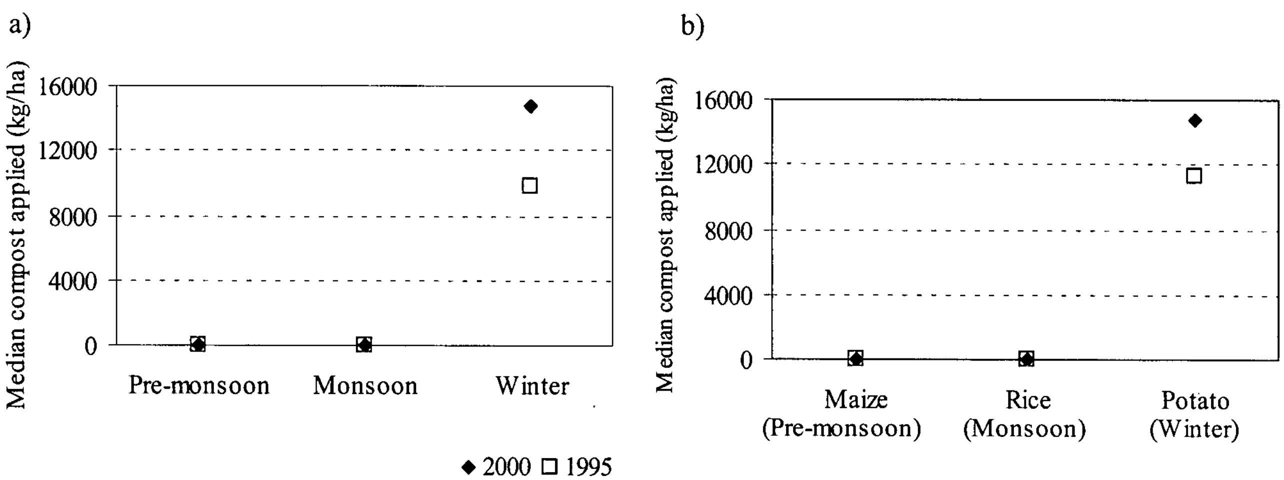


Figure 5.4 Compost additions to intensive khet: a) by season and b) by crop type

Table 5.4 Compost applications to intensive khet fields in 2000.

Khet 2000	Total number growing crops	% of Farmers applying input	Application (kg/ha)		N input (kg/ha)		P input (kg/ha)		K input (kg/ha)	
Compost	N	%	median	range	median	range	median	range	median	range
Monsoon* (Rice)	26	8	0	0-4914	0	0-47	0	0-5	0	0-42
Winter +	26	96	14742	0-29485	140	0-280	15	0-30	126	0-252
Pre-monsoon: total	26	0	0	-	0	-	0	-	0	
Maize	18	0	0	-	0	-	0	-	0	-
Tomato	5	0	0	-	0	-	0	-	0	-
Annual	-	-	14742	0-29485	140	0-280	15	0-30	126	0-252

* All farmers cultivated rice. + All farmers cultivated potato.

Table 5.5 Compost applications to intensive khet fields in 1995.

Khet 1995	Total number growing crops	% of Farmers applying input	Application (kg/ha)		N input (kg/ha)		P input (kg/ha)		K input (kg/ha)	
Compost	N	%	median	Range	median	range	median	range	median	range
Monsoon* (Rice)	26	23	0	0-27028	0	0-256	0	0-27	0	0-231
Winter	26	77	9828	0-29485	93	0-280	10	0-30	42	0-125
Potato	19	95	11302	0-29485	107	0-280	11	0-30	97	0-252
Wheat	6	17	0	0-9828	0	0-93	0	0-10	0	0-84
Pre-monsoon: total	18	11	0	0-14258	0	0-135	0	0-14	0	0-122
Maize	16	13	0	0-14258	0	0-135	0	0-14	0	0-122
Annual	-	-	12285	0-41285	117	0-392	12	0-42	105	0-353

* All farmers cultivated rice

The number of farmers applying compost in 2000 to pre-monsoon and monsoon crops declined by 11% and 15% respectively from 1995 levels (Table 5.4 and Table 5.5). Again this change in compost application patterns appears to be related to potato cultivation. Farmers cultivating potato in the winter season stated that residual organic matter was used for the following pre-monsoon crop and thus no additional compost was added. In 2000, all farmers cultivated potato as a winter crop (Figure 5.2) subsequently no farmers reported compost additions to pre-monsoon crops. The decline in monsoon applications is likely due to farmers concentrating compost additions on potato at the expense of the rice crop.

Although limitation to compost supply were not specifically addressed in the survey it is evident that the introduction of a 3-crop rotation, more specifically potato, has increased compost use in khet. Considering that compost is in limited supply, it is reasonable to presume that compost is being diverted from other applications (e.g. bari fields, less-intensive fields) to sustain intensive operations.

5.1.7. Compost Use: Intensive bari

Compost is applied in all seasons to intensive bari sites, although median compost inputs are greater during the winter and monsoon seasons (Figure 5.5a). In 2000, the median amounts of compost applied to the three dominant crops, maize, potato, and tomato were equivalent, while in 1995, maize crops received more than potato or tomato (Figure 5.5b). Pre-monsoon compost values are comparatively low (Figure 5.5a) despite high inputs to pre-monsoon tomato crops (Figure 5.5b) as tomato is still cultivated by less than 50 % of the farmers cultivating a pre-monsoon crop. If more farmers adopt this cash crop during the pre-monsoon season, pressure to increase compost inputs is likely to occur. The 5 t/ha increase in the median value of compost applied during the winter season is due to an increase in the number of farmers cultivating potato and tomato rather than wheat (Table 5.6 and Table 5.7). The maximum annual application in 2000 was 55 t/ha, which falls within maximum values reported by other authors for bari sites. The median annual application was 39 t/ha.

The percentage of farmers applying compost to monsoon and pre-monsoon crops remained roughly constant between 1995 and 2000, whereas a 13 % increase occurred in the number of farmers applying compost to winter crops in 2000. This corresponds to a 15 % increase in the number of farmers growing potatoes. Although intensification is altering the quantities and temporal allocation of compost (primarily due to the introduction of potatoes and tomatoes), intensive bari systems continue to maintain a more traditional approach to compost management, utilizing compost in all three seasons. In contrast, intensive khet systems demonstrated greater shifts in both the amounts of compost added and the timing of application between 1995 and 2000.

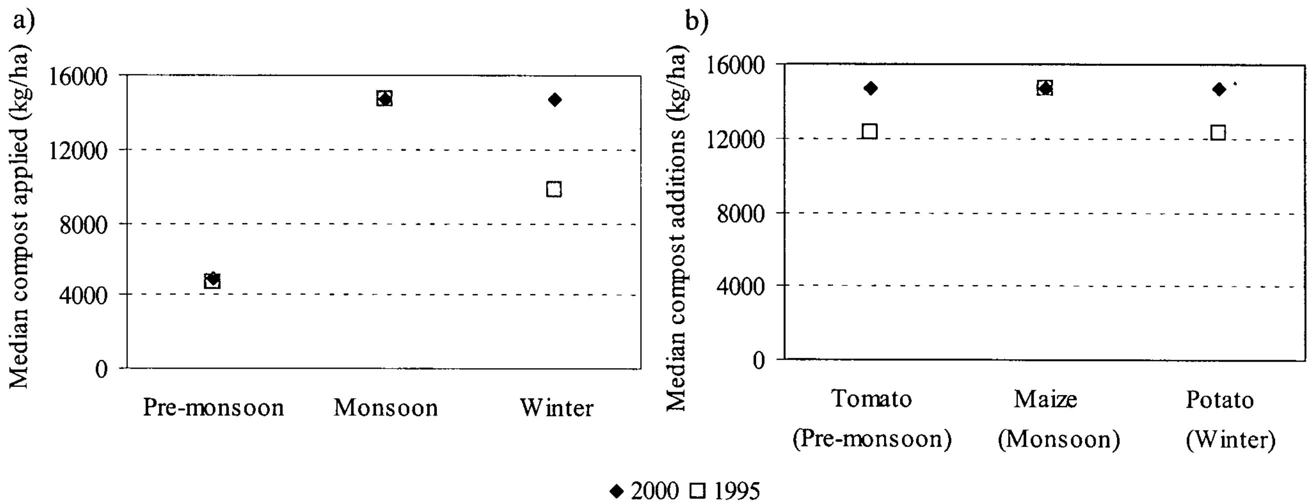


Figure 5.5 Compost additions (kg/ha) to intensive bari by a) season and b) crop type

Table 5.6 Compost applications to bari fields in 2000 for dominant crops.

Bari 2000	Total # growing crops	% applying input	Application (kg/ha)		N input (kg/ha)		P input (kg/ha)		K input (kg/ha)	
Compost	n	%	median	range	median	range	median	range	Median	range
Monsoon* (Maize)	20	90	14742	0-49141	140	0-466	15	0-50	126	0-421
Winter: total	20	80	14742	0-24571	140	0-23s3	15	0-25	126	0-210
Potato	13	100	14742	0-24571	140	0-233	15	0-25	126	0-210
Tomato	5	90	5897	0-24571	56	0-233	6	0-25	50	0-210
Pre-monsoon: total	20	75	4914	0-16217	47	0-154	5	0-16	42	0-139
Tomato	9	100	14742	3440-16217	140	33-154	15	3-16	126	29-139
Wheat	4	25	0	0-3440	0	0-33	0	0-3	0	0-29
Annual			39190	9828-54581	372	93-520	40	10-56	336	84-470

* All farmers grew maize during the monsoon season.

Table 5.7 Compost applications to bari fields in 1995 for dominant crops.

Bari 1995	Total # growing crops	% applying input	Application (kg/ha)		N input (kg/ha)		P input (kg/ha)		K input (kg/ha)	
Compost	n	%	median	range	median	range	median	range	median	Range
Monsoon* (Maize)	18	89	14742	0-32433	140	0-308	15	0-33	126	0-278
Winter: total	18	67	9828	0-14743	93	0-140	10	0-15	84	0-126
Potato	9	100	12286	9828-14743	117	93-140	12	10-15	105	85-126
Wheat	7	14	0	0-9828	0	0-93	0	0-10	0	0-84
Pre-monsoon:	14	79	4644	0-14743	30	0-140	3	0-15	27	0-126
Tomato	6	100	12286	0-14743	117	0-140	12	0-15	105	0-126
Annual			31943	0-49632	303	0-471	32	0-50	273	0-425

* All farmers grew maize during the monsoon season.

5.1.8. Fertilizers

Since the introduction of chemical fertilizers in Nepal in 1965 their application has become an increasingly important component of soil fertility maintenance, particularly as areas attain greater market access. Policy and logistical constraints have heavily influenced fertilizer use in Nepal. Until November 1997, the government Agricultural Inputs Corporation (AIC) maintained control over the importation, marketing, and distribution of all fertilizers within Nepal. Nepali farmers typically faced two issues relating to fertilizer procurement:

1) appropriate types and adequate supplies of necessary fertilizers were unavailable, and
2) fertilizers were too expensive.

These two factors contributed to imbalanced fertilizer use (e.g. dominance of urea), which is known to lead to problems such as soil acidity and micronutrient deficiencies. In an attempt to solve problems associated with fertilizer supply, in November 1999 all fertilizer subsidies were eliminated by the AIC and the involvement of the private sector was encouraged. Fertilizers are currently procured by the AIC, the private sector, and through bilateral/grant assistance programs (Sherchan and Gurung 1995, Fertilizer Advisory, Development, and Information Network for Asia and the Pacific 2001).

The increased use of mineral fertilizers due to better market access, insufficient compost amounts, ease of use, and higher crop rotations, has raised concerns among farmers that the continued application of fertilizers will be unsustainable in the medium to long-term (Pandey *et al.* 1995, Joshi *et al.* 1996, Sherchan *et al.* 1999). Sthapit *et al.* (1988) note that farmers commented on declining soil structure and crop productivity when fertilizer was continuously applied without compost additions. Declines in yield responses have been noted particularly where urea, an acid-generating fertilizer, is predominantly used. Although access to fertilizers has increased over time through better market and road access, the actual availability to farmers is still strongly affected by policy (Basnyat 1999).

5.1.9. Fertilizer use: intensive khet

The amount of fertilizer applied differs by season, which is linked to crop type. The greatest median application of fertilizers is during the winter season (Figure 5.6). Potatoes received the greatest median application in 2000 and in 1995, while wheat received the least. Median applications of fertilizers to potatoes are up to a factor of 9 times greater than fertilizer inputs to rice, tomato, and maize. The percentage of farmers applying fertilizer to winter and pre-monsoon crops increased by 19% and 23 % respectively in 2000 (Table 5.8 and Table 5.9).

Within intensively managed khet systems, N inputs to rice and P inputs to potato are predominantly from fertilizers, while N and P inputs to pre-monsoon crops are entirely from fertilizers in both 2000 and 1995. In contrast, compost provides the greatest source of total potassium to potatoes (Tables 5.4-5.5 and 5.8-5.9).

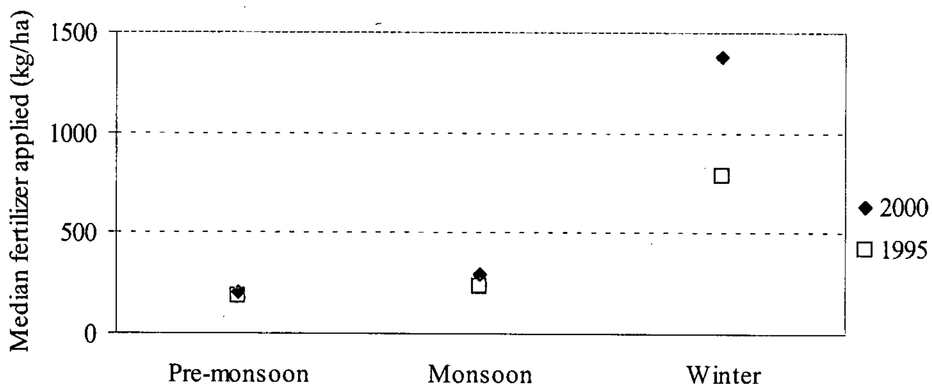


Figure 5.6 Median fertilizer applied to intensive khet sites (by season).

Table 5.8 Chemical fertilizer inputs to khet fields in 2000 for dominant crops.

Khet 2000	Total # growing crops	% applying input	Application (kg/ha)		N input (kg/ha)		P input (kg/ha)		K input (kg/ha)	
Chemical fertilizer	n	%	median	range	median	range	median	Range	median	range
Monsoon* (Rice)	26	92	295	0-786	83	0-279	43	0-118	0	-
Winter+	26	100	1375	727-2948	267	142-580	197	51-393	98	0-245
Pre-monsoon: total	26	88	197	0-851	68	0-226	0	0-170	0	-
Maize	18	78	157	0-491	72	0-226	0	0	0	
Tomato	5	80	236	0-658	42	0-136	39	0-132	0	-
Annual			1946	924-3892	436	187-942	240	157-515	98	0-245

* all farmers cultivated rice, + all farmers cultivated potato

Table 5.9 Chemical fertilizer inputs to khet fields in 1995 for dominant crops.

Khet 1995	Total # growing crops	% applying input	Application (kg/ha)		N input (kg/ha)		P input (kg/ha)		K input (kg/ha)	
Chemical fertilizer	N	%	median	range	median	range	median	Range	median	range
Monsoon* (Rice)	26	100	236	98-491	80	21-181	11	0-47	0	-
Winter	26	81	786	0-2113	193	0-461	64	0-197	0	0-69
Potato	19	100	983	412-2113	197	63-461	86	0-197	0	0-69
Wheat	6	17	0	0-197	0	0-36	0	0-39	0	-
Pre-monsoon: total	18	65	177	0-442	57	0-181	0	0-88	0	-
Maize	16	69	152	0-393	54	0-181	0	0-60	0	-
Annual			1219	138-2349	351	25-628	83	0-236	0	0-69

* all farmers cultivated rice

5.1.10. Fertilizer type: intensive khet

The dominant fertilizers applied in 1995 were urea and complex, whereas in 2000 it was urea and diammonium phosphate (DAP) (Table 5.10). Urea inputs remained relatively constant between 1995 and 2000, whereas large increases in DAP inputs to potato and smaller increases in DAP inputs to rice occurred (Figure 5.7). The number of farmers applying potash to potatoes rose from 4 % in 1995 to 81% in 2000.

Table 5.10 Fertilizer use in khet for dominant crops in 2000 and 1995.

Khet 2000	Crop		Urea (kg/ha)	DAP (kg/ha)	Complex (kg/ha)	Potash (kg/ha)	Ammonium Sulphate (kg/ha)
Monsoon	Rice	Median	143	216	0	0	0
		Range	0-491	0-590	-	-	0-118
Winter	Potato	Median	197	983	0	197	0
		Range	0-688	256-1966	-	0-491	0-197
Premonsoon	Maize	Median	157	0	0	0	0
		Range	0-491	0	-	-	-
	Tomato	Median	0	197	0	0	0
		Range	0-295	0-658	-	-	-
Khet 1995							
Monsoon	Rice	Median	157	0	0	0	0
		Range	0-393	0-236	0-491	-	0-98
Winter	Potato	Median	138	0	786	0	0
		Range	0-295	0-983	0-1966	0-138	0-491
	Wheat	Median	0	0	0	0	0
		Range	0	0-197	-	-	-
Premonsoon	Maize	Median	98	0	0	0	0
		Range	0-393	0-295	0-236	-	-

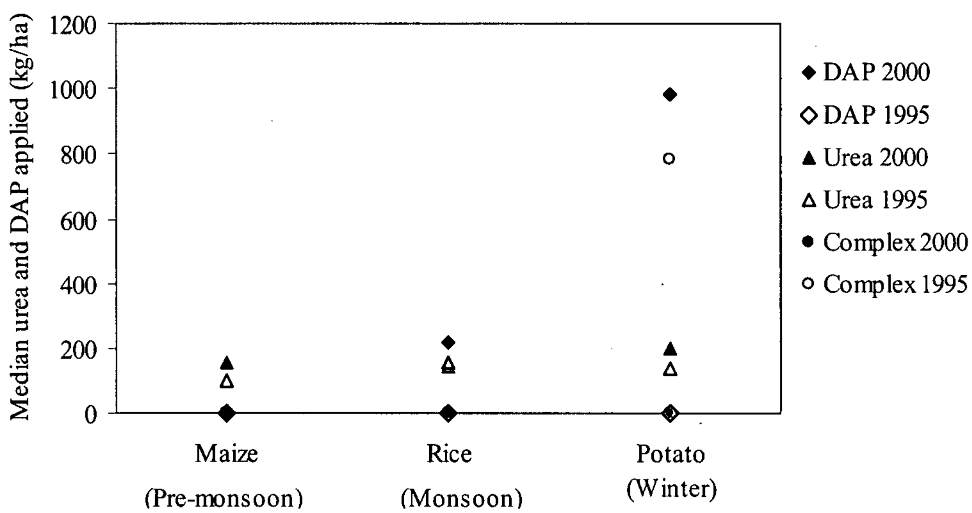


Figure 5.7 Median application of urea and DAP to intensive khet crops in 1995 and 2000.

5.1.11. Fertilizer use: intensive bari

Fertilizer inputs vary by season, with crops grown during the monsoon and winter seasons receiving the highest input rates (Figure 5.8). In contrast to intensive khet sites, median amounts of fertilizers applied during the pre-monsoon and monsoon season increased between 1995 and 2000 rather than remaining constant (Figure 5.8). Crop type also affects the amounts of fertilizers applied. Potatoes received the greatest median application of fertilizers in both 2000 and in 1995 (Table 5.11 and Table 5.12). The greatest increase in the number of farmers applying fertilizers occurred in winter applications, with a 23 % increase between 1995 and 2000 corresponding to a 50% increase in the number of farmers growing cash crops.

In 2000, chemical fertilizers provide a greater proportion of N and P inputs to winter potato, winter tomato, and monsoon maize crops (Tables 5.6 and 5.11). In contrast, K inputs to all crops are entirely from compost inputs. In addition, N inputs to pre-monsoon tomato are predominantly from compost sources (Tables 5.6 and 5.11). In 1995, organic sources of P and K were greater than chemical sources for maize and winter potato (Tables 5.7 and 5.12). Wheat, regardless of season, received the majority of its N, P, and K inputs from chemical sources.

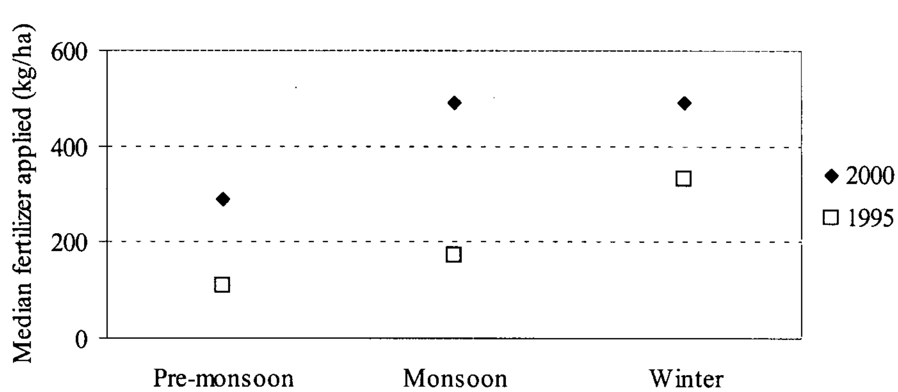


Figure 5.8 Median application of fertilizers to intensive bari sites (by season) in 1995 and 2000.

Table 5.11 Chemical fertilizer inputs to bari fields in 2000 for dominant crops.

Bari 2000	Total # growing crops	% applying input	Application (kg/ha)		N input (kg/ha)		P input (kg/ha)		K input (kg/ha)	
Chemical fertilizer	n	%	median	range	median	range	median	range	median	range
Monsoon* (Maize)	20	100	491	59-1572	201	19-503	18	0-157	0	0-3
Winter: total	20	100	491	118-1376	138	35-316	37	0-98	0	0-392
Potato	13	100	668	118-1376	169	43-314	47	8-98	0	0-117
Tomato	5	100	246	138-1474	83	35-316	22	0-98	0	0-392
Pre-monsoon: total	20	95	290	0-1179	78	0-208	34	0-98	0	0-196
Tomato	9		491	0-1179	88	0-208	51	0-98	0	0-196
Wheat	4		98	0-197	45	0-90	0	-	0	-
Annual			1467	609-2457	414	153-717	96	13-295	0	0-391

*All farmers grew maize during the monsoon season

Table 5.12 Chemical fertilizer inputs to bari fields in 1995 for dominant crops.

Bari 1995	Total # growing crops	% applying input	Application (kg/ha)		N input (kg/ha)		P input (kg/ha)		K input (kg/ha)	
Chemical fertilizer	n	%	median	range	median	range	median	range	median	range
Monsoon* (Maize)	18	100	331	59-885	148	19-285	0	0-98	0	-
Winter: total	18	78	172	0-818	66	0-285	10	0-98	0	-
Potato	9	100	491	98-818	126	34-285	29	8-98	0	-
Wheat	7	43	0	0-126	0	0-101	0	0-31	0	-
Pre-monsoon: total	14	86	108	0-1535	50	0-472	12	0-167	0	-
Tomato	6		500	98-818	146	29-252	68	12-98	0	-
Annual			698	59-2518	253	19-775	43	0-274	0	0-98

*All farmers grew maize during the monsoon season

5.1.12. Fertilizer type: intensive bari

The dominant fertilizers applied to bari fields are urea and DAP in both 2000 and 1995. Complex and potash use is limited in both years (Table 5.13). Changes in the amounts of urea and DAP applied in 1995 and 2000 differ between the three dominant crops. Urea inputs to tomatoes declined while DAP inputs increased from 1995 levels. In contrast, urea and DAP inputs to maize increased from 1995 levels, while urea and DAP inputs to potato are equivalent in both years (Figure 5.9). In summary, farmer's use of DAP and urea varies with crop type.

Table 5.13 Fertilizer use in bari for dominant crops in 2000 and 1995.

Bari 2000	Crop		Urea (kg/ha)	DAP (kg/ha)	Complex (kg/ha)	Potash (kg/ha)	Ammonium Sulphate (kg/ha)
Monsoon	Maize	Median	442	86	0	0	0
		Range	0-826	0-786	0-197	-	-
Winter	Potato	Median	236	236	0	0	0
		Range	79-491	0-983	0-983	0-236	-
	Tomato	Median	34	152	0	0	0
		Range	0-688	0-491	Na	-	-
Premonsoon	Tomato	Median	157	353	0	0	0
		Range	0-491	0-491	-	0-393	-
	Wheat	Median	147	0	0	0	0
		Range	98-491	-	-	-	-
Bari 1995							
Monsoon	Maize	Median	295	0	0	0	0
		Range	0-491	0-491	0-79	-	-
Winter	Potato	Median	236	236	0	0	0
		Range	59-983	0-983	0-334	-	-
	Wheat	Median	0	0	0	0	0
		Range	0-147	0-983	0-49	-	-
Premonsoon	Tomato	Median	381	214	0	0	0
		Range	0-688	0-983	0	0-197	-

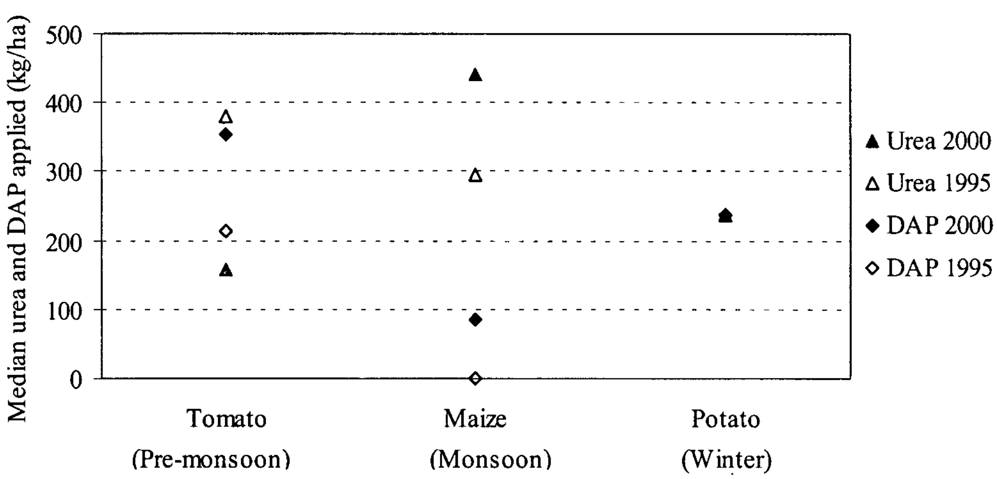


Figure 5.9 Median inputs of urea and DAP to dominant intensive bari crops in 1995 and 2000.

5.2. Soil erosion

Soil erosion and the resultant redistribution of sediments represent a loss of nutrient from bari systems and nutrient enrichment to khet systems, as topsoil erosion occurs primarily in upland bari sites and in marginal lands. Carver (1997) determined that the majority of surface sediment nutrient losses in a headwater system occurred during 1 or 2 pre-monsoon storm events before vegetative cover was established. The sediment nutrient losses from these events may represent up to 75-95% of the total annual loss. However, half of all sediment production is returned to long-term storage within the basin as bari and khet ditches may re-capture up to 30 % and 60% respectively of the total sediment production which is then deposited on lowland fields. Erosion results in a significant re-distribution of nutrient-rich sediments from bari to khet areas. The net effect of this sediment deposition is that khet soils are enriched in C, P, Ca, Mg, K and pH at the expense of bari soils (Wymann 1991, Carver 1997).

5.3. Socio-economic factors

The underlying socio-economic factors that influence nutrient inputs and thus soil fertility in the Jhikhu Khola valley are land tenure, poverty, culture, and population growth. Farmers with secure land tenure and where subsistence requirements were met invest more in soil fertility. Similarly, economic well being is positively correlated with nutrient inputs. Caste influences soil fertility as it may influence the quality of land owned, access to capital, and whether nutrient inputs are preferentially applied to khet or bari. Population growth negatively impacts soil fertility as it results in greater pressure on forest resources, increased expansion onto marginal lands, and land-use intensification without adequate inputs (Brown 1997)

5.4. Land-Use Type

Agricultural land-use may be divided into khet and bari. Brown (1997) determined land-use to be the most important factor determining soil fertility. Similar to results obtained by Schreier *et al.* (1994), khet soils had higher pH, exchangeable Ca, base saturation and available P than bari soils. In contrast, exchangeable K, C, and N were greater in bari than khet. Wymann (1991) and Vaidya *et al.* (1995) observed comparable results.

Khet land benefited from the addition of nutrient-enriched sediments within irrigation waters and the alkalinity of the irrigation water itself, which impacts soil pH. The higher levels of organic carbon and nitrogen in bari were due to the greater compost inputs (Schreier *et al.* 1994).

5.5. Summary: Nutrient flows

Nutrient flows into soils are affected by soil erosion, socio-economics, land use type and nutrient management. Soil erosion results in nutrient depletion from upland bari sites and subsequent enrichment to khet land. Economic well being and secure land tenure contribute positively to nutrient flows. The cropping pattern, the quality of compost, and fertilizer availability all influence nutrient management. The cropping intensity and the types of crops grown affect the magnitude and temporal application of compost and fertilizer use. In khet, compost applications vary by season, with limited applications to monsoon and pre-monsoon crops, whereas in bari compost is applied throughout the year, with monsoon and winter crops receiving the majority of inputs.

Chemical fertilizers are predominantly applied to the winter potato crop in khet fields with DAP applied in the greatest quantities. Fertilizer applications to monsoon maize and winter potato crops were equivalent in intensive bari sites in 2000. Between 1995 and 2000, DAP applications increased for maize and tomato crops, while urea inputs to tomato declined, but increased for maize. Compost use and chemical fertilizer use has increased in both khet and bari accompanied by an increasing dominance of cash crops, specifically potato.

6. TYPES AND AMOUNTS OF INPUTS

To understand the potential effects of agricultural intensification on soil fertility an understanding of how farmers are modifying and adjusting fertilizer and compost inputs is needed. The following sections will examine:

1) the changes in inputs between 1995 and 2000 that occurred within intensive khet and bari (triple crop rotation) systems.
2) differences in inputs between intensive khet and bari sites
3) the changes in inputs between less-intensive (double crop rotation, sampled in 1994) and intensive sites.

The combination of previous studies and this study provides a unique opportunity to document how intensification is affecting input types and amounts within the Jhikhu Khola watershed.

6.1. Khet Inputs: 2000 versus 1995

Figure 6.1 to Figure 6.3 depict total inputs, chemical inputs and organic inputs of nitrogen, phosphorus, and potassium for intensive khet fields surveyed. The figures also depict the relative contribution of chemical versus organic sources of the respective nutrients.

Total inputs of nitrogen, phosphorus, and potassium were significantly greater in 2000 than in 1995 ($\alpha = 0.05$). Chemical inputs of all three nutrients increased significantly during this period, while organic inputs remained constant (Figure 6.1 to Figure 6.3).

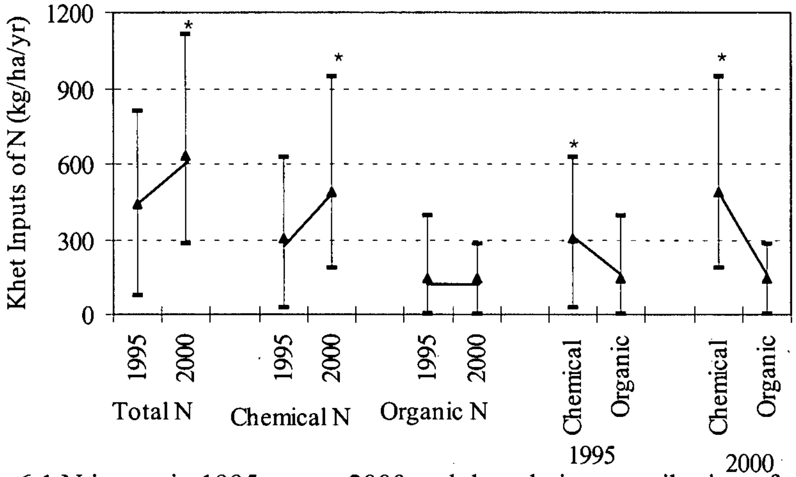


Figure 6.1 N inputs in 1995 versus 2000 and the relative contribution of chemical versus organic sources to intensive khet sites. Mean (▲), minimum, and maximum. (* = significant difference at $\alpha < 0.05$, MWU).

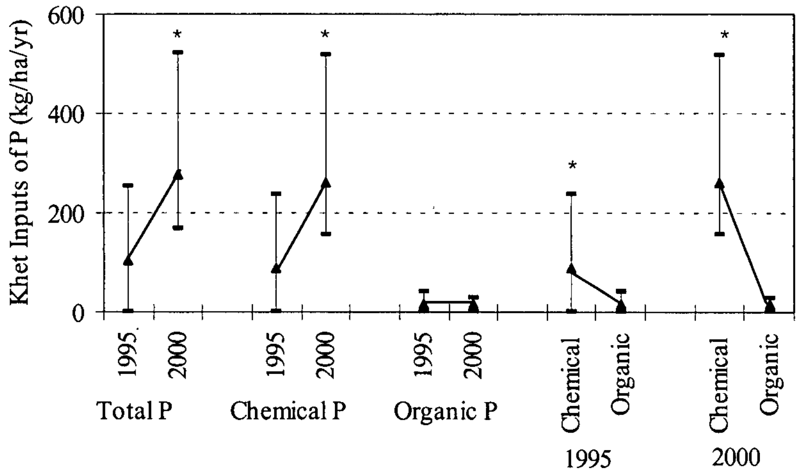


Figure 6.2 P inputs in 1995 versus 2000 and the relative contribution of chemical versus organic sources to intensive khet sites. Mean (▲), minimum, and maximum. (* = significant difference at $\alpha < 0.05$, MWU).

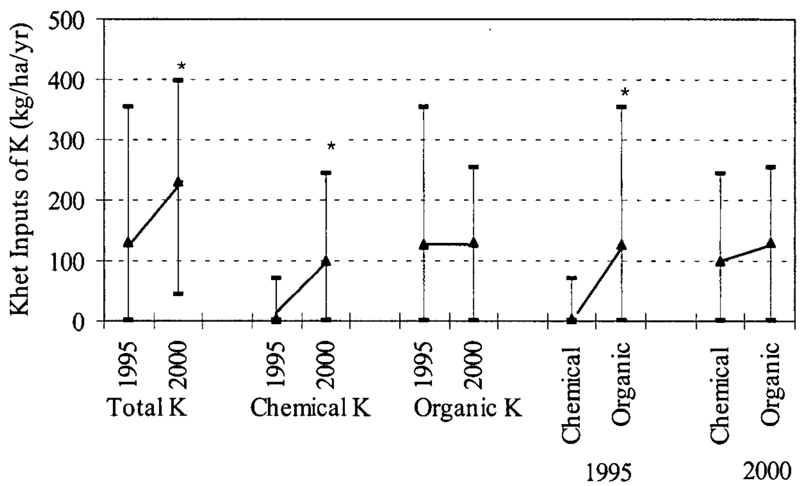


Figure 6.3 K inputs in 1995 versus 2000 and the relative contribution of chemical versus organic sources to intensive khet sites. Mean (▲), minimum, and maximum. (* = significant difference at $\alpha < 0.05$, MWU).

Chemical sources of nitrogen and phosphorus contributed significantly more to total inputs than organic sources in both 2000 and 1995. In contrast, chemical sources of potassium where significantly less than organic sources in 1995, however, by 2000 chemical sources increased such that levels were not statistically different to organic inputs.

Overall fertilizer use increased significantly between 1995 and 2000. Specifically, inputs of urea, DAP, and potash significantly increased from 1995 levels, while complex inputs decreased (Figure 6.4).

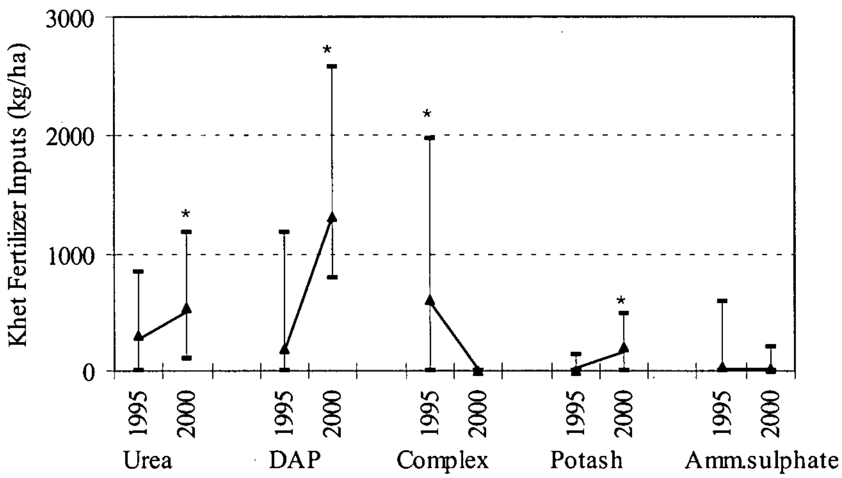


Figure 6.4 Fertilizer input by type in 2000 vs. 1995 to intensive khet sites. Mean (▲), minimum, and maximum. (* = significant difference at $\alpha < 0.05$, Mann-Whitney U).

Lack of timely access to fertilizers was mentioned by only one farmer asked for reasons for a lack of crop increase. However, the decline in the use of complex and the consequent increase in DAP use is linked to availability. After 1995/1996 the AIC no longer sold complex fertilizer (Fertilizer Advisory, Development, and Information Network for Asia and the Pacific 2001), thus availability would be entirely dependent on private suppliers. This is evident in Figure 6.4 which shows inputs of complex declining to zero by 2000 and a significant increase in DAP from 1995 onwards. This policy issue has greater implications in terms of P inputs. DAP will contribute roughly double the amount of chemical P to the soil as an equivalent amount of complex since the NPK ratio of DAP is 18:46:0, while that of complex is only 20:20:0. Thus, farmers are not only increasing their fertilizer use with intensification, they are doubling their P inputs through the use of DAP, providing a direct link between policy and soil fertility.

As potash was available prior to 1995, the significant increase in its use may be due to increased farmer awareness of the high nutrient extraction of potassium by potato (Ahmad 1977, Dean 1994). A weak positive correlation (r^2 = 0.29, Spearman's rho) exists between potato yield and potash use in 2000, supporting the notion that farmers have observed a positive feedback loop between potash use and potato yield.

Compost inputs did not vary significantly between 1995 and 2000. Farmers surveyed were not specifically asked whether compost availability was a limiting factor. Thus no exclusive explanation may be given for the lack of increase in compost inputs at a time when farmers increased fertilizer use, presumably to meet greater crop nutrient requirements. This may indicate that farmers do not have additional supplies of compost due to intensification, or simply that (as mentioned by some farmers) constraints associated with time, proximity to home, and amount of land holdings prevented additional compost use or resulted in preferential use of fertilizers. In summary, within intensive khet fields significantly greater inputs of N, P, and K have occurred through time, however this has been due to increases in chemical sources, primarily urea and DAP, and to a lesser extent potash rather than compost.

6.1.1. Bari: Inputs for intensive sites in 1995 and 2000

In contrast to khet sites, intensive bari sites only had significantly greater amounts of total N and chemical N ($\alpha < 0.05$) in 2000 versus 1995 (Figure 6.5). Total P, chemical P, and total K inputs were significantly greater ($\alpha < 0.10$) in 2000 (Figure 6.6). No statistical difference ($\alpha < 0.05$) was observed between 1995 and 2000 levels for inputs of organic N, P, and K, and chemical forms of K (Figure 6.5 to Figure 6.7)

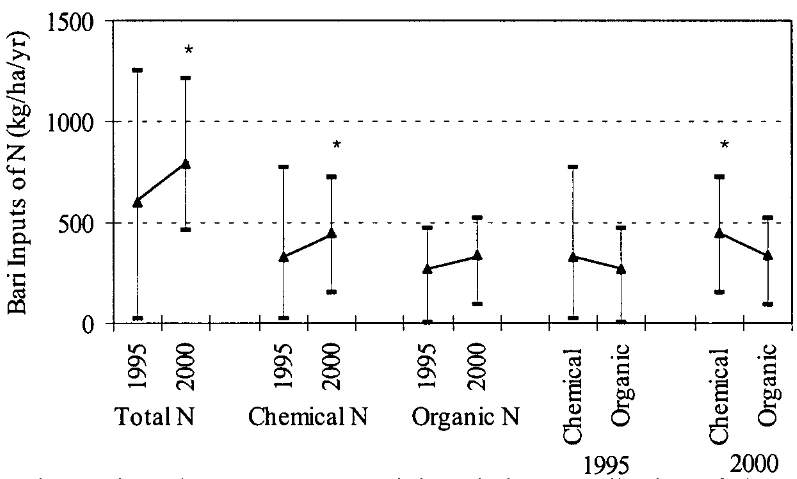


Figure 6.5 N inputs in 1995 versus 2000 and the relative contribution of chemical versus organic sources to intensive bari sites. Mean (▲), minimum, and maximum. (* = significant difference at $\alpha < 0.05$, Mann- Whitney U).

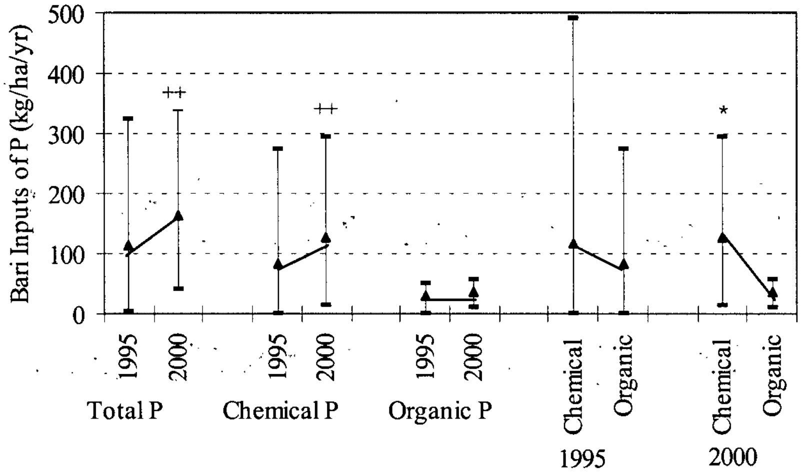


Figure 6.6 P inputs in 1995 versus 2000 and the relative contribution of chemical versus organic sources to intensive bari sites. Mean (▲), minimum, and maximum. (++ = significant difference at $\alpha < 0.10$, Mann Whitney U).

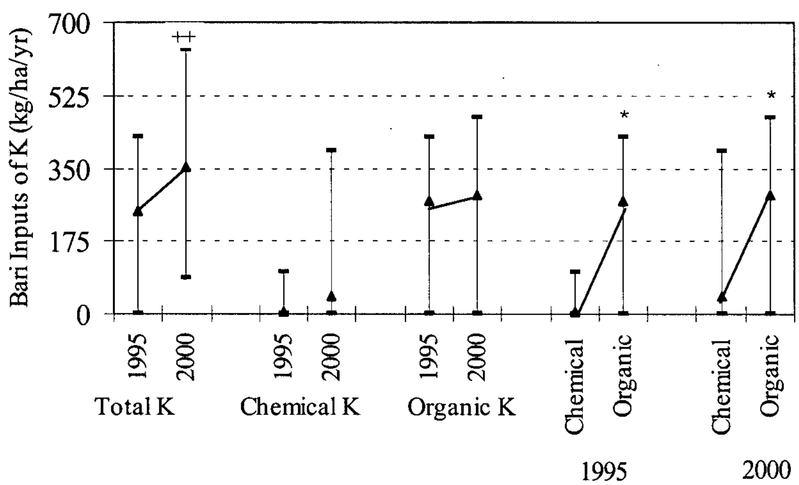


Figure 6.7 K inputs in 1995 versus 2000 and the relative contribution of chemical versus organic sources to intensive Bari sites. Mean (▲), minimum, and maximum. (++ = significant difference at $\alpha < 0.10$, * = significant difference at $\alpha < 0.05$, Mann Whitney U).

The relative contribution of chemical to organic sources varies between the nutrients. Chemical nitrogen and phosphorus inputs are significantly greater than organic inputs in 2000, a shift from 1995 when contributions from both chemical and organic sources are approximately equivalent (Figure 6.5 and Figure 6.6). Organic sources of potassium contribute significantly more than chemical sources of K in both 1995 and 2000. This is because very few farmers use potash as a fertilizer in bari sites (4 of 23 in 2000 and only 1 farmer in 1995), and thus K inputs are almost entirely from compost additions.

Total fertilizer inputs are significantly greater in 2000 than in 1995 to bari sites. However, within individual fertilizer types only urea inputs exhibited a significant increase in 2000 at $\alpha < 0.10$. All other fertilizer types exhibit a trend of increasing mean inputs (Figure 6.8).

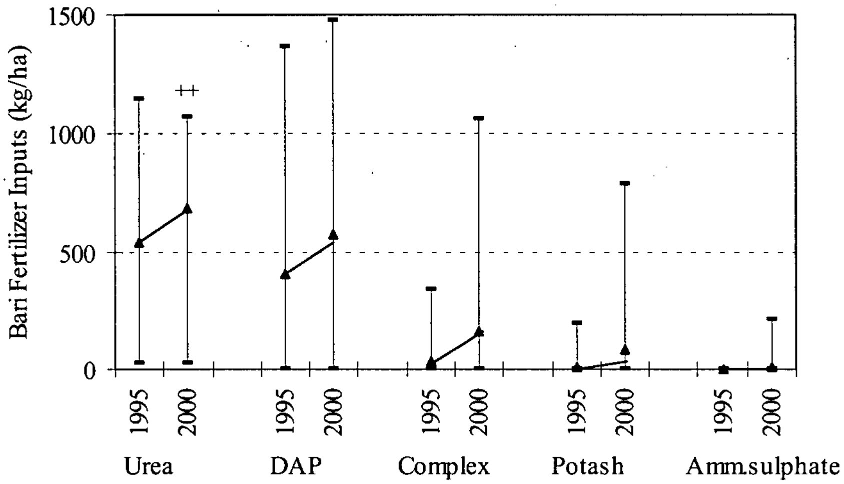


Figure 6.8 Inputs of various fertilizer types in 2000 compared to 1995 for intensive bari sites. Mean (▲), minimum, and maximum (++ = significant difference at $\alpha < 0.10$, Mann Whitney U).

The amount of compost applied in 2000 and 1995 was not significantly different and significant increases in total N and P are due to fertilizer sources.

6.2. Inputs: Intensive khet versus intensive bari

Fertilizer inputs between khet and bari were not significantly different in 1995, however, by 2000 khet sites used significantly more fertilizer than bari sites (Figure 6.9). In contrast, bari sites had significantly greater compost inputs than khet sites in both 1995 and 2000 (Figure 6.10).

Similar changes in fertilizer use are occurring in bari as in khet sites, however at a smaller scale. An inverse trend occurred in compost use; khet sites exhibited smaller increases than bari. The mean amount of compost used in intensive bari sites increased by 7 t/ha over the 5 year period while for khet sites this was only 0.2 t/ha. This underlies the well-documented fact that traditionally khet sites have a stronger dependence on chemical inputs and bari sites on compost inputs, a trend that has persisted despite intensification.

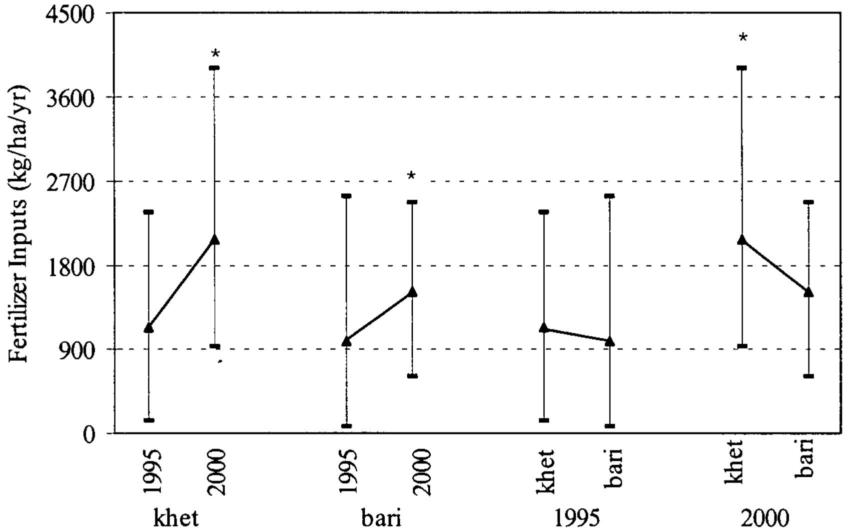


Figure 6.9 Fertilizer inputs for intensive khet and bari sites in 1995 and 2000. Mean (▲), minimum, and maximum. (* = significant difference at α < 0.05, Mann Whitney U).

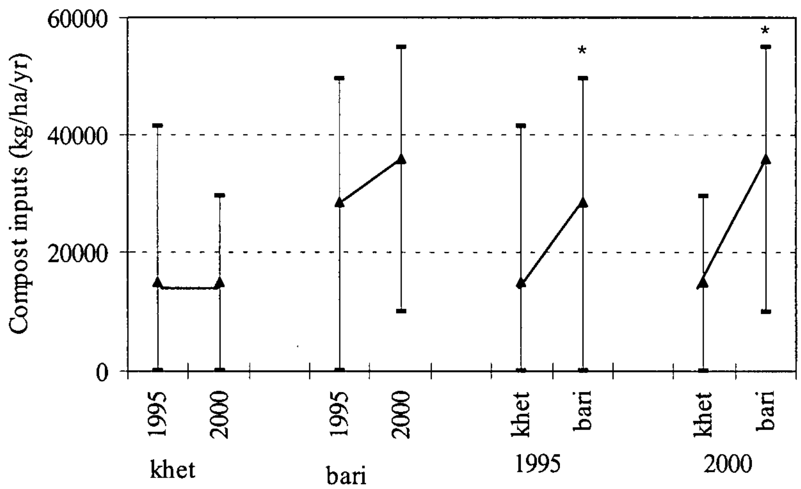


Figure 6.10 Compost inputs for intensive khet and bari sites in 1995 and 2000. Mean (▲), minimum, and maximum. (* = significant difference at α < 0.05, Mann Whitney U).

Use of specific fertilizer types also differed between khet and bari in 2000 (Figure 6.11) and in 1995 (Figure 6.12). Khet sites received significantly greater inputs of DAP and potash than bari sites in 2000, whereas complex use was significantly greater in bari.

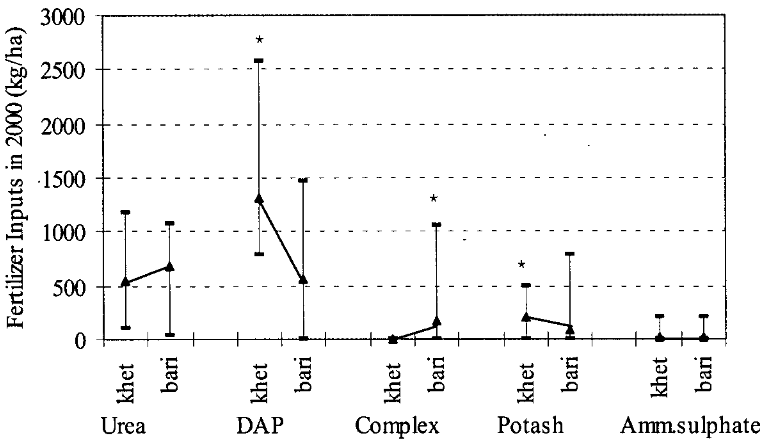


Figure 6.11 Relative amounts of fertilizer types applied to intensive khet and bari sites in 2000. Mean (▲), minimum, and maximum. (* = significant difference at $\alpha < 0.05$, Mann Whitney U).

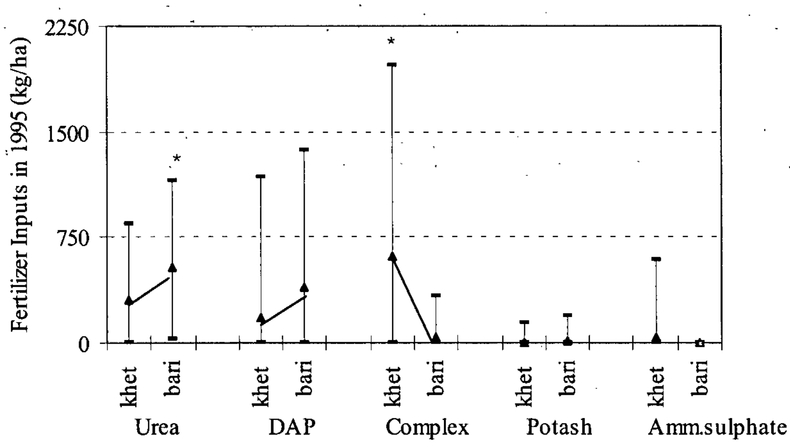


Figure 6.12 Relative amounts of fertilizer types applied to intensive khet and bari sites in 1995. Mean (▲), minimum, and maximum (* = significant difference at $\alpha < 0.05$, Mann Whitney U).

The use of complex fertilizer was significantly greater in khet than in bari in 1995, while urea use was greater in bari (Figure 6.12). The sum of fertilizer and compost usage patterns in 2000 resulted in intensive bari fields receiving significantly greater amounts of nitrogen and potassium inputs than khet (Fig. 6.13), whereas khet received greater inputs of phosphorus (Fig 6.13). In 1995, significant differences in nutrients were only evident in total potassium, with bari sites receiving significantly more potassium than khet sites. The greater total inputs of nitrogen and potassium in 2000 in bari compared to khet, indicates the importance of large amounts of compost additions, despite the low percent nutrient content of compost, to nutrient flows.

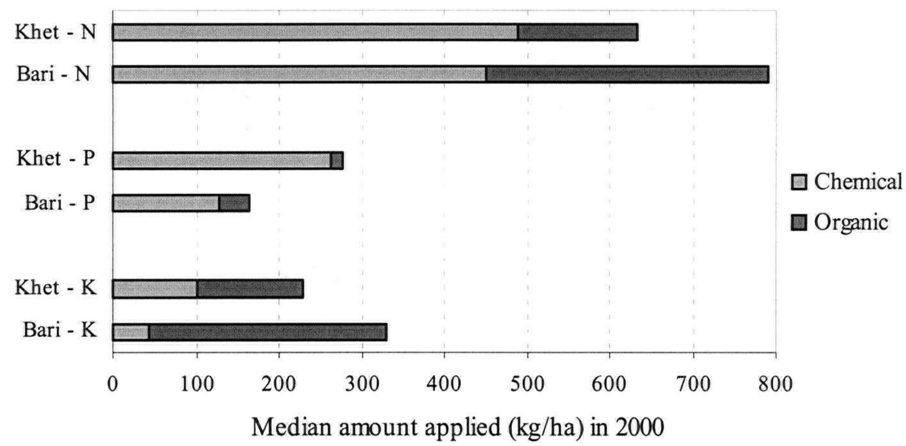


Figure 6.13 Median amounts of fertilizer and compost applied to intensive khet and bari sites in 2000.

6.3. Inputs: intensive versus less-intensive sites

Intensification places greater demand on soil nutrients not only because more crops are being grown per year, but also because typically more nutrient demanding crops are being grown. Farms under intensive management tend to cultivate more nutrient demanding cash crops (e.g. potato and tomato) than farms managed less-intensively (Figure 5.2 and Figure 5.3). Farmers therefore need to increase total inputs of N, P, and K under intensive farming to avoid mining the soil nutrient pool. Within the Jhikhu Khola watershed farmers have modified input levels with intensification. Intensive sites received significantly greater fertilizer (Figure 6.14) and compost (Figure 6.15) inputs than less-intensive sites for both khet and bari, in both 1995 and 2000. This resulted in significantly greater amounts of total, chemical, and organic N, P, and K inputs to intensive sites.

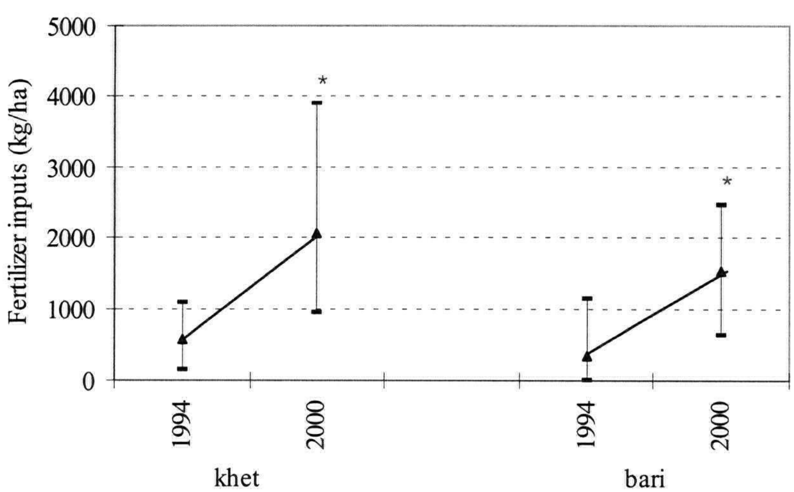


Figure 6.14 Fertilizer inputs to intensive (1995 and 2000) and less-intensive sites (1994). Mean (▲), minimum, and maximum (* = significant difference at $\alpha < 0.05$).

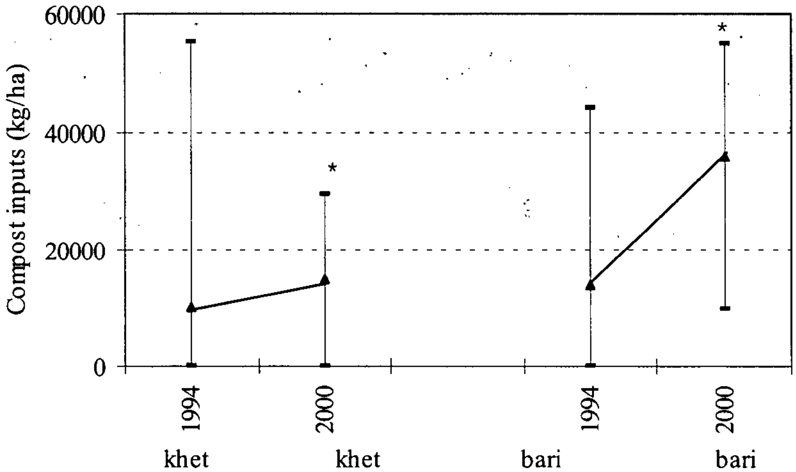


Figure 6.15 Compost inputs to intensive (1995 and 2000) and less-intensive sites (1994). Mean (▲), minimum, and maximum (* = significant difference at $\alpha < 0.05$).

Although total inputs of nitrogen, phosphorus, and potassium have increased significantly demonstrating that farmers are changing inputs with intensification, a nutrient budget is necessary to determine whether the increase in inputs are sufficient to meet the additional crop nutrient demands.

6.4. Summary: Input amounts and types

Within intensive khet sites, changes in chemical inputs have occurred in the 5-year time period from 1995 to 2000. Urea, DAP and potash use have all increased significantly contributing towards a significant increase in the total inputs of N, P, and K. The rise in DAP is due to the government's supply policy, whereas, the rise in potash use is likely linked to greater farmer knowledge of the nutrient requirements of potato. Compost additions have remained constant for intensive khet sites. Compost additions to intensive bari sites appear to be increasing, although the difference in inputs between 2000 and 1995 is not statistically significant. It is probable that limitations in compost availability or greater ease in transporting fertilizers or a combination of these and other factors prevent statistically significant increases in the application of compost inputs.

Within intensive bari sites, there is a significant increase in fertilizer use due to a significant rise in urea use, as well as a trend of increasing mean fertilizer use for other fertilizer types. The mean amount of compost applied did not increase significantly between 1995 and 2000.

Intensive khet systems received significantly more fertilizer than bari in 2000, while intensive bari systems received significantly more compost inputs than khet in both 1995 and2000. This highlights the differences in how the different land uses meet their nutrient requirements. Similar to traditional nutrient management patterns, bari systems have increased compost inputs while khet systems have increased fertilizer inputs. Farmers have responded to intensification by significantly increasing compost and fertilizer inputs from input levels used within less intensive farming systems. Given that compost supplies are limited it is likely that compost supplies are being diverted from less-intensively managed sites to support the nutrient requirements of intensive farming systems. The significant rise in fertilizer use justifies concerns of soil acidification, although given that compost use has also increased, acidification effects may be buffered. A nutrient budget, as discussed in chapter 5, will examine whether the increase in inputs is adequate to meet greater crop nutrient uptake.

7. NUTRIENT BUDGETS

A nutrient budget is simply the difference between nutrient flows into (inputs) and nutrient flows out of (losses) a defined agricultural system. A positive balance indicates nutrient enrichment to the system while a negative balance indicates nutrient depletion. In this study, a field-level nutrient budget is calculated for khet and bari fields for nitrogen, phosphorus, and potassium to assess whether soil nutrient pools are being maintained for all 20 bari and all 26 khet fields. A limitation to examining each nutrient in a separate budget is that interactions between nutrients are not specifically addressed (e.g. whether the excess of a particular nutrient is due to the shortage of another (Janssen 1999)).

Nutrient inputs into cropping systems may include fertilizer sources, compost, biological fixation, sediment additions, and irrigation water. Nutrient losses may result from crop uptake, chemical sorption-desorption processes, mineralization-immobilisation, leaching, chemical fixation, erosion processes, denitrification, and volatilisation. Relevant inputs and outputs used to calculate individual nutrient cycles (Figure 7.1 - Figure 7.3) will vary between the nutrients. Numerical values for the assumptions within N and P nutrient budgets (e.g. fertilizer efficiency) were obtained from Brown (1997), while those for potassium were obtained from literature sources.

Due to the prevalence of micas, soil potassium levels historically have not been a limiting factor within the Middle-Mountains and typically nutrient budgets for potassium were not calculated. However experiences with intensification in other regions has led to K deficiencies in soil where levels have previously been considered adequate. As potato, a particularly demanding crop in terms of potassium uptake, is synonymous with intensification in the Jhikhu Khola, and because increased inputs of nitrogen and phosphorus will stimulate greater overall nutrient uptake, a potassium budget was included to explore the potential changes in K with intensification.

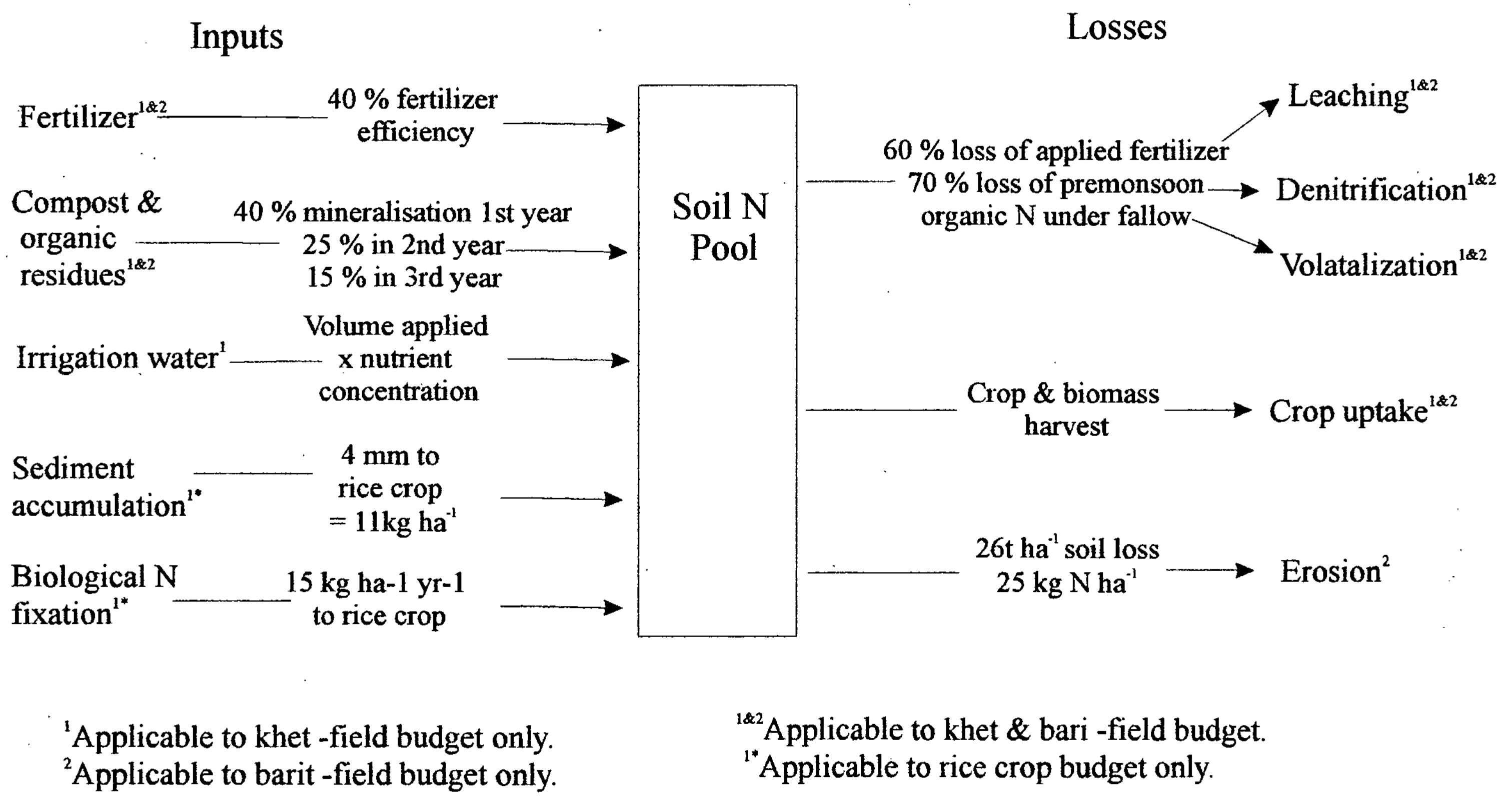
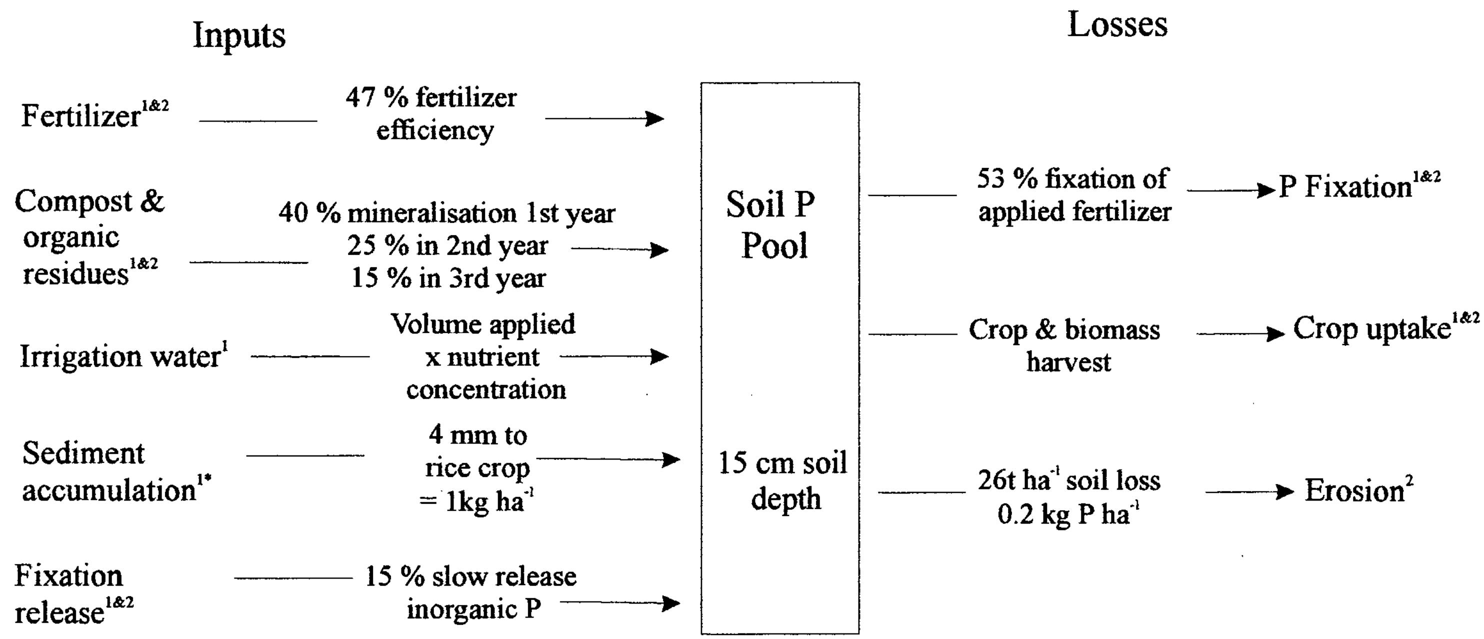


Figure 7.1. Framework for model used to determine nitrogen nutrient balance.



[1]Applicable to khet -field budget only.
[2]Applicable to barit -field budget only.

[1&2]Applicable to khet & bari -field budget.
[1*]Applicable to rice crop budget only.

Figure 7.2 Framework for model used to determine phosphorous nutrient balance.

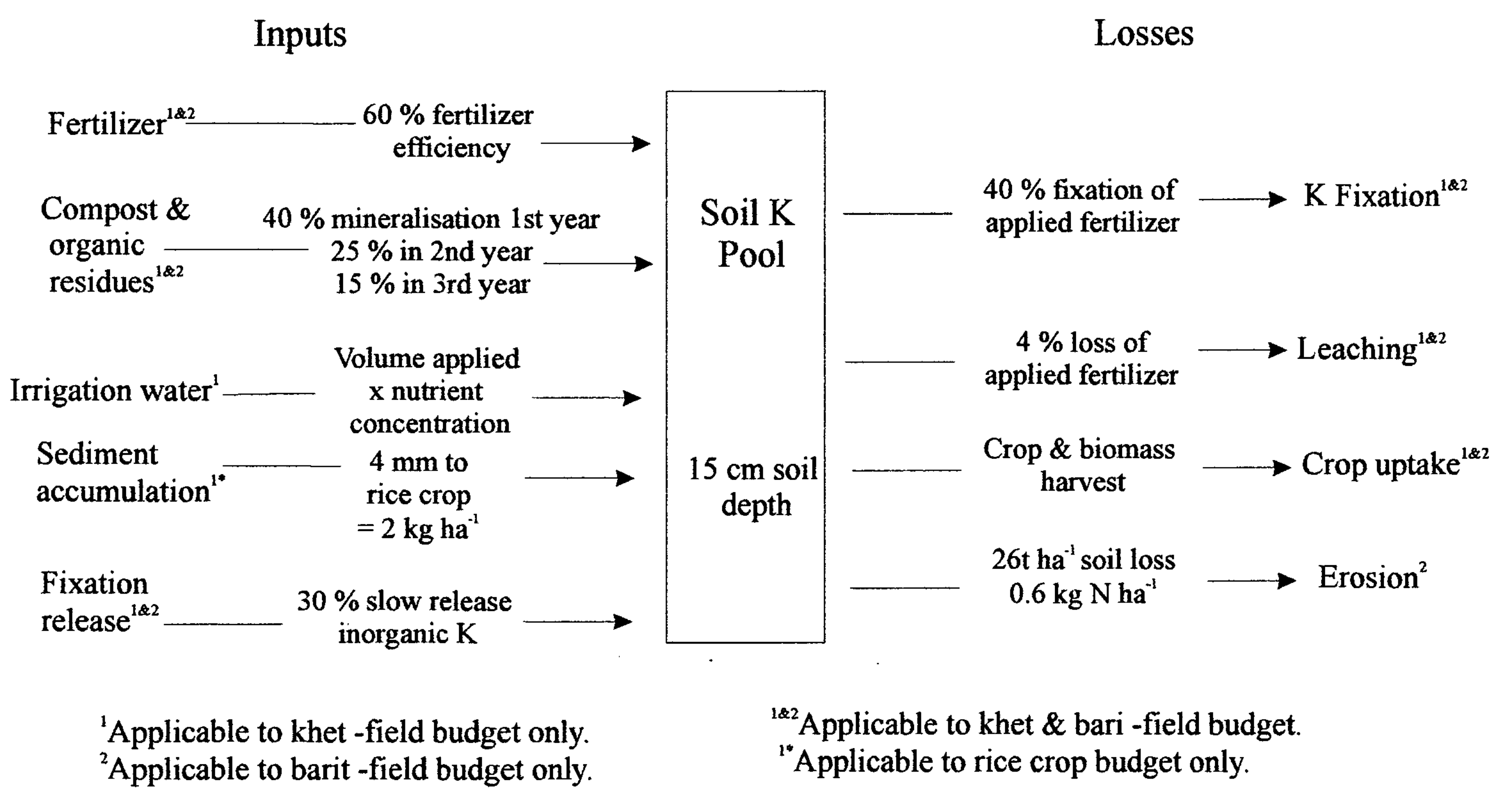


Figure 7.3 Framework for model used to determine potassium nutrient balance.

7.1. Fertilizer Inputs

Typical fertilizer inputs rates are summarized in Table 5.8 to Table 5.12. The following discussion will focus on the fate of nitrogen, phosphorus, and potassium added to the soil by fertilizer inputs.

7.1.1. Nitrogen

Nitrogen is a mobile element for which the supply of plant available forms (ammonia (NH_4^+) and nitrate (NO_3^-)) is dependent upon inorganic fertilizer inputs and the release from organically bound soil N. Urea is the predominant inorganic N source in developing countries and provides nitrogen as NH_4^+. When urea is applied to the soil surface, ammonia may undergo a hydrolysis process converting it into free ammonia gas (NH_3) within 1-4 days resulting in considerable losses. Incorporating urea into the topsoil may minimize these gaseous losses.

Ammonia may also undergo an oxidation process by microorganisms converting it into nitrate. As nitrate is negatively charged it is not well retained by soil colloids and thus may be leached from the soil, depending upon application rates and rainfall/irrigation intensity. Thus, nitrogenous fertilizers typically only have an efficiency of 30-50% of total applied. Nitrogenous fertilizer efficiency was assumed to be 40% for the nutrient budget (Tisdale and Nelson 1966, Sanchez 1976, Cooke 1982, Simpson 1986, Brown 1997).

7.1.2. Phosphorus

Available forms of phosphorus are typically very low particularly in weathered tropical soils. Phosphate added to soils by fertilizers is generally rapidly fixed, although a small portion may become re-available with time due to mychorrhizal fungi and other microorganisms. Phosphorus fixation and transformation between forms is primarily controlled by pH. With increasing acidity, relatively insoluble Fe- and Al-phosphates are formed. Soils with a higher content of Fe and Al oxides and exchangeable Al will fix more phosphate than less acidic, silicate-based mineralogy (Sanchez 1976). As determined by Brown (1997) fixation by Fe and Al oxides was assumed to be 53% of applied fertilizer P on non-red soils, with a subsequent slow release of 15% per annum by chemical and microbial processes.

7.1.3. Potassium

Depending upon a variety of factors, potassium fertilizer additions may be leached, fixed, and/ or slowly re-released from soils. Soil type, crop cover, degree of fixation and rainfall/irrigation intensity affect potassium losses due to leaching. Generally leaching losses are considered to be low, except in sandy or coarse textured soils with low CEC combined with high rainfall and/ or over-irrigation. Crop cover will reduce leaching losses through plant uptake (Ataga 1974, Tandon and Sekhon 1988, Cox and Uribe 1992, Yläranta *et al.* 1996, Oyanarte *et al.* 1997, Askegaard and Eriksen 2000, Duwig *et al.* 2000).

Askegaard and Eriksen (2000) observed leaching rates of only 0.2% despite high (988kg/ha) applications of K. Poss *et al* (1997) observed leaching rates of 2% in kaolinite-dominated soils due to low levels of exchangeable K, while leaching rates for West Africa were usually less than 10%. In Sweden, Ulén (1999) observed leaching rates from clay soils of 7-14%. Based on the clay content, the estimated mineralogical composition, and the time of application, a leaching rate of 4% was assumed for the nutrient budget.

Fixation involves the conversion of either exchangeable K^+ or soil K^+ into non-exchangeable forms. Factors controlling fixation include clay mineralogy, soil moisture, temperature, the degree of saturation of specific K binding sites, fertilizer rates, fertilizer history, pH, and the extent of weathering of minerals. Fixation is greater in soils with large amounts of mica and/or illites and in soils high in 2:1 clays than in soils with a high kaolinite content. Wetting and drying cycles increase K fixation in 2:1 clays. As in the case of P, large additions of K fertilizer over long time periods will reduce fixation of subsequent applications and lead to an increase in the content of exchangeable K. The influence of pH on K fixation is indirect, largely controlling which cation predominates the inter-layer positions of clay minerals (Tisdale and Nelson 1966, van Diest 1978, Malavolta 1985, Khan *et al.* 1994, Rubio and Gil-Sotres 1996, Poss *et al* 1997, Sardi and Csitari 1998).

Due to the variety of site-specific influencing factors, a wide range of fixation rates may be encountered in the literature. Poss *et al.* (1997) observed fixation values of 20%, Page *et al.* (1963) determined fixation to be 63-76%, Acquaye (1974) determined the mean fixation for 48 African soils to be ~ 20%, with a range of fixation values between 0.5% to 62.4%, Malavolta (1985) reported average fixation values for tropical and subtropical soils of 17% and 24% after wetting and drying respectively. Based on these and other sources and the micaceous nature of the soils a fixation value of 40% was assumed for the model.

Although fixation of K into non-exchangeable forms decreases the effectiveness of fertilization on the immediate time-scale, due to the dynamic nature of the equilibrium between exchangeable, non-exchangeable, and soil solution K (Figure 7.4), the release of non-exchangeable potassium (both from fertilizer and from sources inherent within the soil) can be a substantial source of nutrients on a longer time scale. In addition, fixation minimizes losses due to leaching. Fixation and release processes are an important buffer to the level of soil solution and exchangeable K within soils.

Soil solution K^+ $\rightleftharpoons$ Exchangeable K^+ $\rightleftharpoons$ Non-exchangeable K^+

Figure 7:4 Equilibrium between soil solution, exchangeable and non-exchangeable pools of K+.

The rate and magnitude of K release from non-exchangeable sources is primarily dependent upon the type and amount of clay minerals present and the levels of exchangeable and soil solution K. Other factors that influence release are climate, temperature, particle size, pH, soil structure, and other cations within the soil solution and plant roots.

Illite and micaceous clays with interlayer K are a major source of non-exchangeable K, which can become available to plants. Release is a diffusion controlled processes, thus as levels of exchangeable and soil solution K are decreased (by plant uptake or leaching), release of non-exchangeable K occurs. With increasing concentration of available K the rate of release will be inhibited. In laboratory experiments, Malavolta (1985) reported that the release of structural K from illite and muscovite to the soil solution only occurred after concentrations were less than 0.25 and 0.0025 mmol/L respectively.

In addition, positive correlations exist between pH and release. The rate of release will determine the degree to which K will be available for plant uptake, although different crops vary in their ability to utilize slowly available K. Species with an extensive root system, low growth rate, and high affinity for K^+ in the absorption process are more capable of using K^+ from non-exchangeable sources. This is particularly relevant in soils with severely depleted levels of K, as in these instances most of the potassium comes from non-exchangeable sources. (Dowdy and Hutcheson 1963, Tisdale and Nelson 1966, Ataga 1974, Martin and Sparks 1983, Malavolta 1985, Onchere *et al.* 1989, Rao and Khera 1994, Liu *et al.* 1997).

The exact nature of the equilibrium between non-exchangeable and exchangeable K is system specific and dependent upon the crops grown. The values presented in the following text are to give the reader a sense of amounts and rates of release, in one year, observed in different settings. Oyanarte *et al.* (1997) recorded slow liberation rates of 30 kg/ha in the Basque Country. Ataga (1974), working in Nigeria, determined 59 kg/ha of plant available K to come from non-exchangeable sources in acidic soils, while in soils derived from Basement complex non-exchangeable sources of K contributed 155 kg/ha. Talati *et al.* (1974) observed the release of 200-385 kg/ha of non-exchangeable K from a sandy loam in Rajasthan.

In a three year legume-grass experiment under K stressed conditions 24 % of total K removed by the crop was from non-exchangeable sources (van Diest 1978). In contrast, Rao and Khera (1994) report that non-exchangeable sources in Delhi soils contributed over 87% of total plant uptake when soils were at minimal exchangeable K levels. Part of the difference in the values is that in the latter experiment, Sudan grass was used, a much more nutrient extractive plant than the legume-grass mix used in the former. Ataga (1974) observed a 46% release of fixed K within two weeks for Nigerian soils.

Release rates were obtained from Verma (1963), Dowdy and Hutcheson (1963) and Rao and Khera (1994) to calculate hypothetical release rates for a hectare furrow slice of Jhikhu Khola soils (Table 7.1). Soils were estimated to have a clay content of 30% of which 40% is micaceous with a K content of 6 %. The measured median bulk density (1235 kg/m^3 (n=171)) of all soils sampled was used. It should be noted that the rate provided by Verma (1963) was measured for the initial 15-day cropping period and represents a theoretical maximum rate, while in the case of the two latter authors it is the average rate for the entire cropping duration and may thus be a more realistic measure of potential release.

A 30 % rate of release of K fixed from fertilizer sources was assumed for khet fields and a 20 % rate of release for bari fields. Releases from structural sources of non-exchangeable K are not included in the budget as the objective is to determine if the management practices are sustainable with respect to the soil nutrient pool.

Table 7.1 Potential release amounts of non-exchangeable K for Jhikhu Khola soils under varying release rates.

Release rate (day^{-1})	Total released: 270 days (kg/ha x 15 cm)	Total released: 365 days (kg/ha x 15 cm)	Soil characteristics	Source
91µg/g of mineral	325	440	Illite	Verma (1963)
0.25 mg/kg of soil[a]	125	170	% Illite: 34 % Clay: 9.7 CEC: 10.9 pH: 8.4	Rao and Khera (1994)
0.67 mg/kg of soil[b]	335	450	% Illite: 9 % Clay: 20 CEC: 6.3 pH: 8.4	*Ibid*
0.47 mg/kg of soil[c]	235	320	-	*Ibid*
0.14 mg/kg of soil[a]	70	100	% Illite: 15 % Kaolinite:15 pH: 6.6 CEC: 12.85	Dowdy and Hutcheson (1963), Cook and Hutcheson (1960)
1.1 mg/kg of soil[b]	570	770	% Illite: 20 % Kaolinite:15 pH: 5.9 CEC: 14.88	*Ibid*
0.63 mg/kg of soil[c]	310	420	-	*Ibid*

[a] minimum value for all soils within study
[b] maximum value for all soils within study
[c] average value for all soils within study[c]

7.2. Compost Additions

Mineralization rates for N, P, and K were assumed to be 40% in the first year, 25% in the second year, and 15% in the third year as in Brown (1997).

7.2.1. Nitrogen

Nitrogen losses from handling and preparation of compost were discussed earlier (see Section 5.1.3). Once incorporated into the soil, organic matter provides a slowly available N source through mineralization processes. Mineralization rates will depend on temperature, C:N ratios, pH, clay mineralogy, and soil moisture content. Wetting and drying cycles increase mineralization rates as do an increase in temperature and a decline in C:N ratios. Although organic sources of N provide a source of nitrogen, due to the low concentrations of N within compost (1.93 %) large volumes are required to reach recommended application rates (Sanchez 1976, Brady 1990). N losses under fallow are assumed to be 70% (Brown 1997).

7.2.2. Phosphorus and Potassium

Organic forms of phosphorus may account for up to 50% of total soil P. Soil microbes may mineralise P releasing it into the soil solution where it may be taken up by plants or fixed into inorganic forms. Microbial breakdown can provide a slow release of P over time (Sanchez 1976, Brady 1990).

Negative charge on organic matter is capable of electrostatically binding K^+ ions. The degree to which this occurs is pH dependent. Although organic matter may retain K+ in the exchangeable form, it has no capacity to fix K into non-exchangeable forms (Tisdale and Nelson 1966, Malavolta 1985).

7.3. Erosion

Average rates of erosion from bari sites, as measured by Carver (1997), were 26 ± 5 t/ha. This value, combined with the nutrient content of eroded sediment and residual soils, was used to estimate annual losses from bari sites (Table 7.2). Annual losses of N, P, and K were 25 kg/ha, 0.2 kg/ha, and 0.6 kg/ha respectively. No erosion was assumed to occur on khet sites.

Table 7.2 Nutrient losses from bari sites due to eroded sediments.

Variable	Nutrient content (mg/kg)		Erosion		Depth Integrated Losses (kg/ha per soil loss depth)		
	Eroded	Residual	Rate (t/ha)	Soil loss (mm)	Eroded	Residual	Losses
			26 ± 5	2			
N	1882	941			49	24	25
P	27.9	20.5			0.72	0.53	0.19
K	100	77			2.6	2.0	0.6

[1] data source: Carver 1997

7.4. Irrigation water

The addition of irrigation water and the associated nutrient-enriched suspended sediments contributes positively to the nutrient budgets of khet fields (Wymann 1991, Carver 1997).

Irrigation water contributes 6 kg N/ha, 1 kg P/ha and 28 kg K/ ha for a one-hectare crop of rice, assuming a water application depth of 0.5 m, 3 times per crop. Inputs were calculated for a potato crop assuming that furrows comprised ¼ of a hectare and were filled with a 0.2 m water depth, 7 times per cropping season. Irrigation water contributed 1.4 kg/ha, 0.3 kg/ha, and 6.5 kg/ha of N, P, and K respectively (Table 7.3).

Flooding of rice fields provides an additional source of nitrogen as cyanobacteria fix N in the water column and on the submerged soil surface. For a more detailed discussion of this refer to Brown (1997). A value of 15 kg/ha/yr due to biological N fixation was assumed for the rice crop as determined by Brown (1997).

Table 7.3 Estimated nutrient inputs due to irrigation of rice and potato crops in khet fields.

Variable	Spring[1]	Stream[1]	Annual inputs to a rice crop		Annual inputs to a potato crop	
			Nutrient	kg/ha	Nutrient	kg/ha
NO_3 (mg/L)	1.7	1.9	N	6.1	N	1.4
PO_4 (mg/L)	0.25	0.26	P	1.2	P	0.3
K (mg/L)	1.9	1.8	K	27.8	K	6.5
Ca (mg/L)	20.1	20.0	Ca	300	Ca	70
PH	8.2	8.7	-	-	-	-

[1] data source: Schreier *et al.* 1994

Sediments carried by irrigation water are nutrient enriched and their deposition onto the fields as they settle from flood irrigation of rice crops provides an additional nutrient input to khet fields. Annual nutrient inputs to khet fields from suspended sediment were calculated assuming a 4mm depth of deposited sediment, a bulk density of 1400 kg/m^3, and measured median nutrient concentration obtained from Schreier *et al.* (1994) (Table 7.4).

Table 7.4 Estimated nutrient inputs to khet fields due to sediment deposition from irrigation waters.

Variable	Median Nutrient Concentration[1]		Annual Inputs (kg/ha for a 4mm soil depth)		
	Accumulated	Residual	Accumulated	Residual	Enrichment
C (%)	0.73	0.56			
N[2] (%)	0.07	0.05	39.2	28.0	11.2
Available P (mg/kg)	32.6	13.5	1.8	0.8	1.0
Exchangeable K (mg/kg)	82.1	46.9	4.6	2.6	2.0
Exchangeable Ca (mg/kg)	2273	1776	127	99	28

[1] data source: Shah and Schreier 1995b
[2] % N calculated from correlation with % C

7.5. Nutrient removal by crops

Crop type, variety, and yield will all influence the amount of nutrients required and removed. With intensified cropping practices, the introduction of high yielding varieties, and increased use of fertilizers, greater crop yields may be attained. This increases the amount of nutrients plants are removing from the soil. Crop nutrient input requirements are typically higher than the nutrient removal by crops due to the loss of applied nutrients through fixation, leaching and other losses (Jian-Chang and Hasegawa 1985, FAO 2000b).

Nutrient removal by crop uptake was determined using the % nutrient content of individual crops, as obtained from literature sources, combined with reported farmer yield data (Table 5.2), and a harvested portion: whole plant (HP: WP) ratio. Whole plant refers to the aboveground plant part and the below-ground harvested portion where appropriate. In Middle Hill farming systems crop residues are removed from the fields to be used as animal feed and thus calculating whole-plant removals is justified.

Table 7.5 provides the percent nutrient composition and the HP: WP ratios used to calculate crop-specific nutrient uptake. Individual references for the data may be found in Appendices 3 to 9.

Table 7.5 Percent nutrient composition and harvested portion: whole plant yield of main crops.

Crop	HP:WP ratio	%N	%P	%K
Rice	2.34	1.0	0.17	0.83
Maize	2.19	1.4	0.26	1.16
Wheat	2.23	1.2	0.22	0.75
Potato	1.41	0.48	0.07	0.77
Tomato	1.25	0.30	0.04	0.40

The HP:WP ratio values for the main cereal crops correspond to values presented by Pilbeam *et al.* (2000) for major cereal crops grown in the Middle-Mountains of Nepal.

7.6. Khet Nutrient Budgets

Nutrient budgets for both khet and bari fields were calculated for:

1) individual fields.
2) a median farm for the main cropping pattern cultivated.

Figure 7.1 to Figure 7.3 illustrate the framework of the model used to respectively calculate the nitrogen, phosphorus, and potassium budgets. When interpreting the budgets it is important to note that the fields represented for 2000 and 1995 are different from those in 1994, although the data set does represent the change in budgets as farms move from less-intensive (1994) to intensive (1995 and 2000).

7.6.1. Khet Individual farm budgets

Changes in the nitrogen, phosphorus, and potassium budgets of individual farms are evident with intensification. Two trends exist for khet nitrogen budgets. There is a 31 % increase in the number of farms that have a negative N balance between less-intensive (1994) and intensive farms (2000). In addition, the value for the maximum surplus obtained decreased, while the value for the maximum deficit attained increased as farms shifted from a less-intensive crop rotation to an intensive crop rotation. This pattern is repeated within intensive sites through time (1995 vs. 2000) (Figure 7.5).

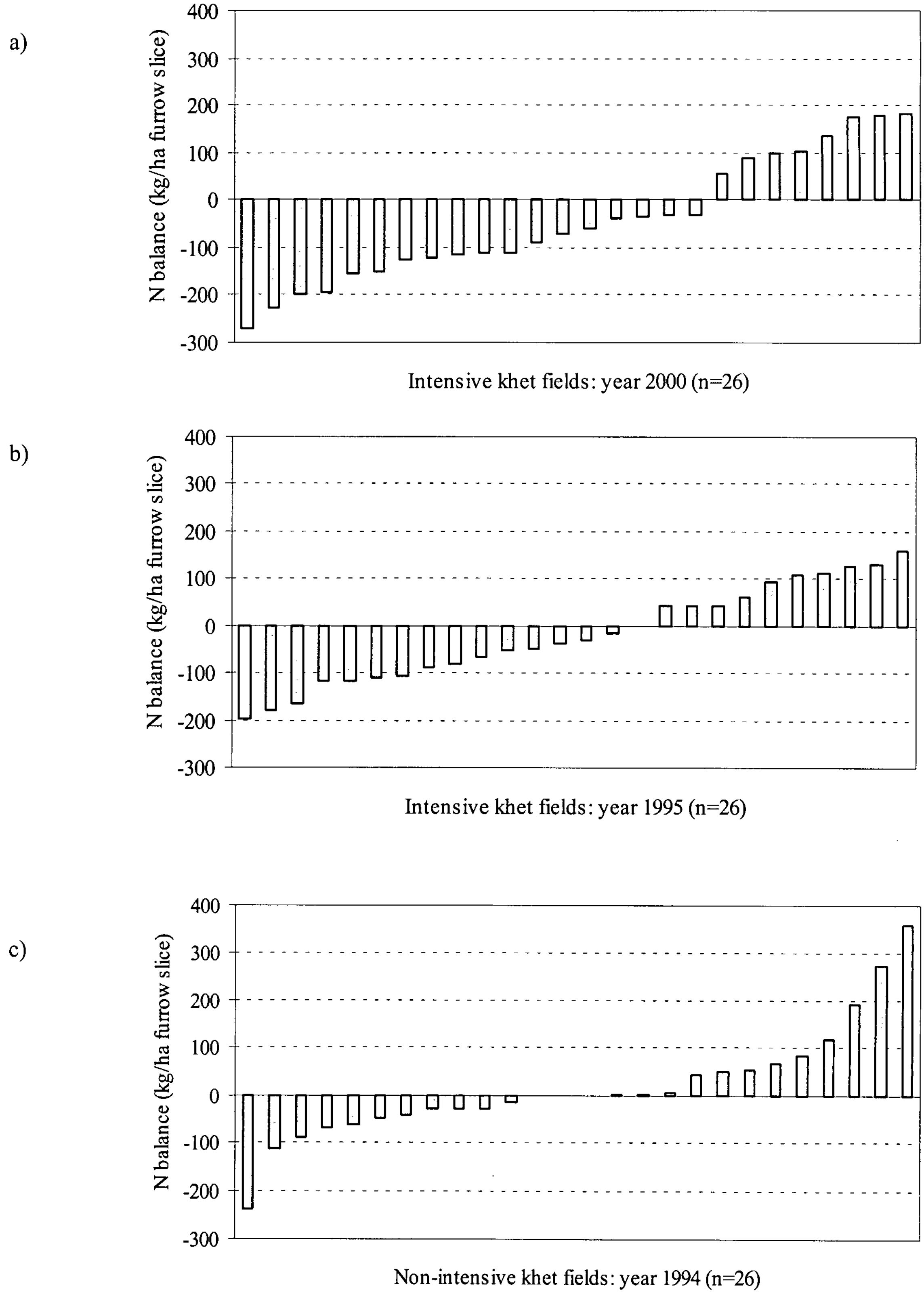


Figure 7.5(a-c) Nitrogen budget for individual khet fields.

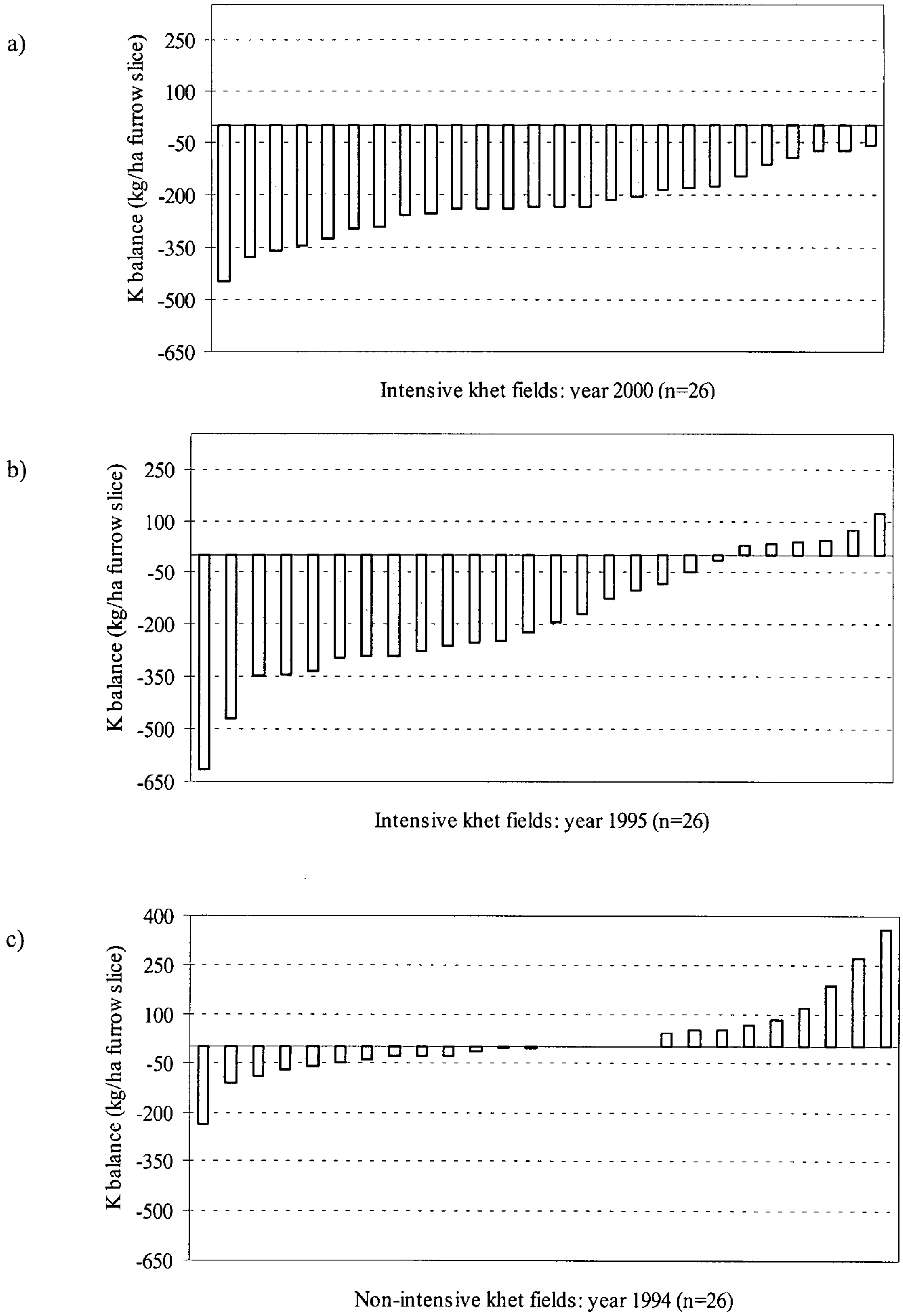


Figure 7.6 (a-c) Potassium budget for individual khet fields

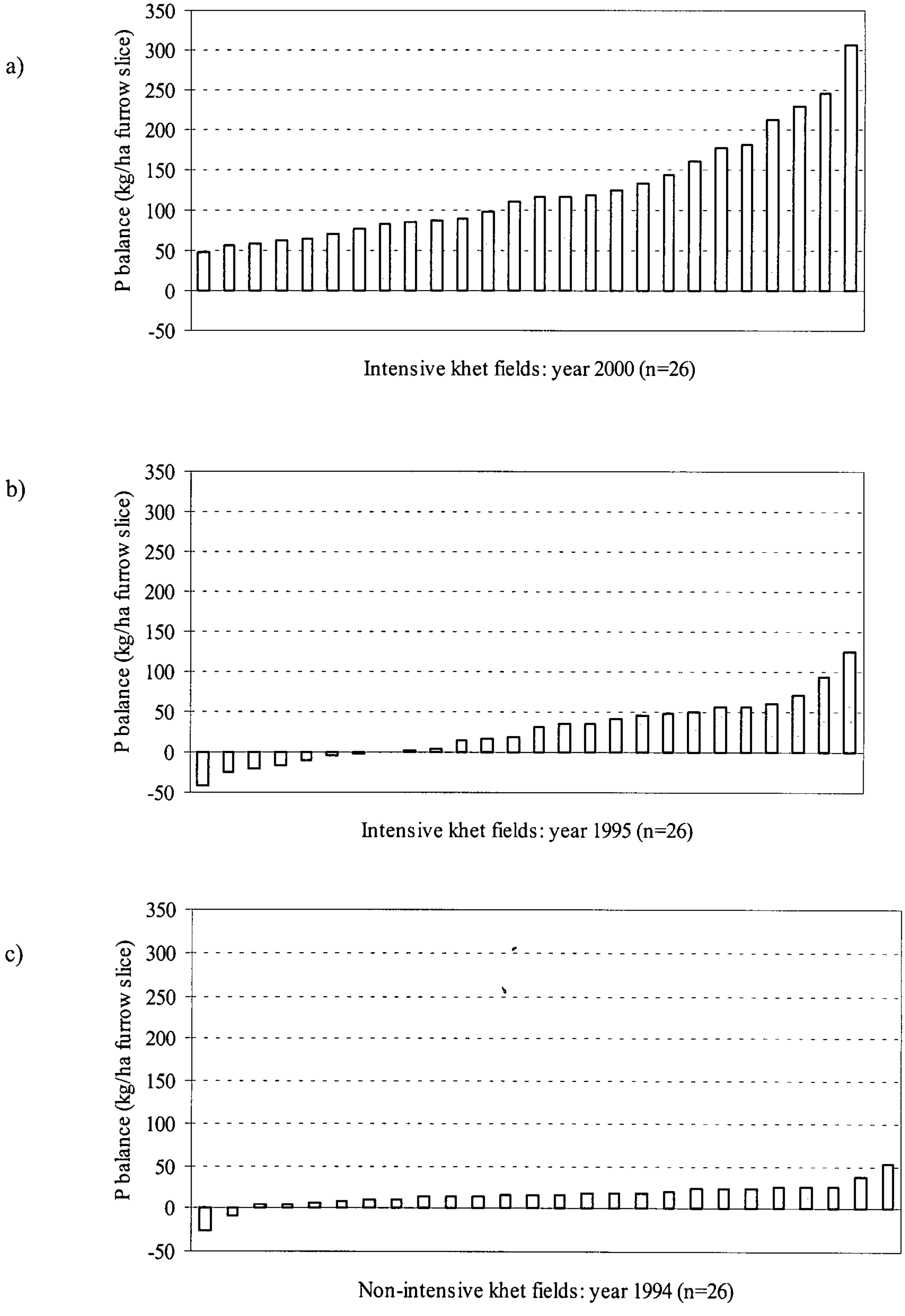


Figure 7.7 (a-c) Phosphorus budget for individual khet fields.

The effects of intensification on potassium budgets are similar to nitrogen, although more dramatic. Under less-intensive management in 1994, 13 farms (50%) had positive K budgets; by 2000 no farms maintained a positive budget. In addition, a considerable decline in the value of the maximum deficit occurred (Figure 7.5). The maximum deficit increased from - 239kg/ha to - 447 kg/ha from less-intensive to intensive systems.

Between 1995 and 2000 within intensive sites, the number of farms with a negative K budget increased, however, the extremes in the deficit values have been reduced. This is due to the significant increase in potash use and compost in 2000 compared to 1995, positively impacting K budgets.

Trends within phosphorus budgets are opposite to those of nitrogen and potassium. Intensification has resulted in all khet farms having positive budgets and resulted in an increase in the magnitude of the P surplus. The maximum P budget surplus increased from 53 kg/ha in 1994 to 305 kg/ha in 2000 (Figure 7.7). Within intensive sites a similar pattern of increasing P surplus occurs between 1995 and 2000.

7.6.2. Median budgets: based on dominant crop rotation

The dominant cropping rotation for khet fields in 2000 is a rice-potato-maize rotation, while in 1994 it is a rice-wheat-fallow rotation. The median N, P, and K nutrient budgets for farms cultivating the respective rotations are presented in Figure 7.8. Compost inputs refer to the total nutrients within the organic matter applied to a crop rotation, organic residues refer to the inputs received from previous crop rotations, while organic retention refers to compost that was not decomposed during the year of application. Chemical losses for nitrogen refer to leaching, denitrification, and volatilization processes. Fixation release refers to the slow release of inorganic fertilizer from Al and Fe oxides in the case of P fixation and from non-exchangeable sources in the case of K fixation.

Figure 7.8 illustrates the changes in specific inputs and losses as farms shift from a rice-wheat-fallow cropping rotation to a rice-potato-maize rotation in terms of nitrogen, phosphorus, and potassium budgets. The median nitrogen budget of a rice-potato-maize crop rotation has a slightly (-53 kg/ha) negative budget (Figure 7.8a). Intensive sites have greater fertilizer and compost inputs with correspondingly higher losses due to organic retention and chemical losses (denitrification etc.).

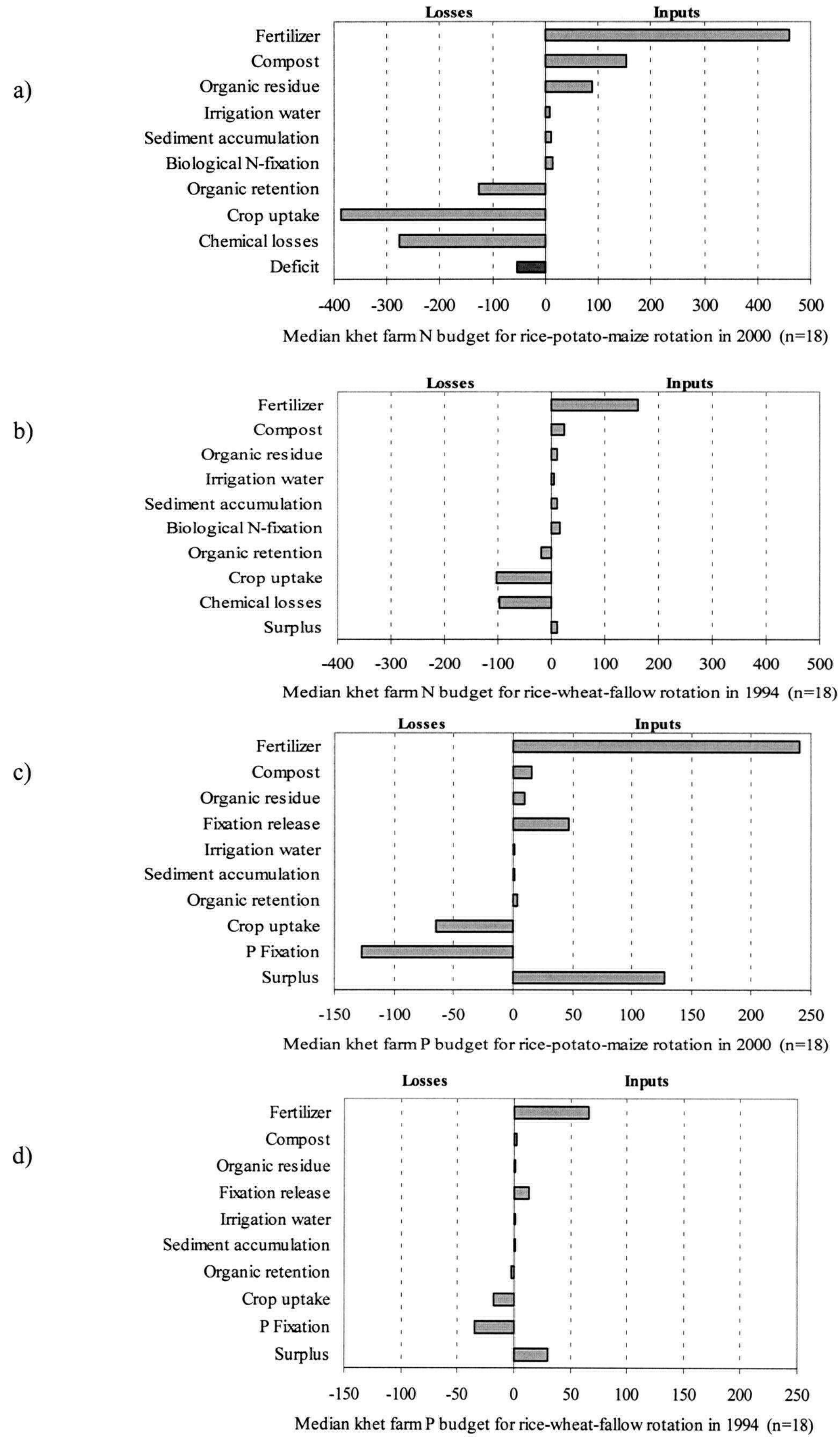
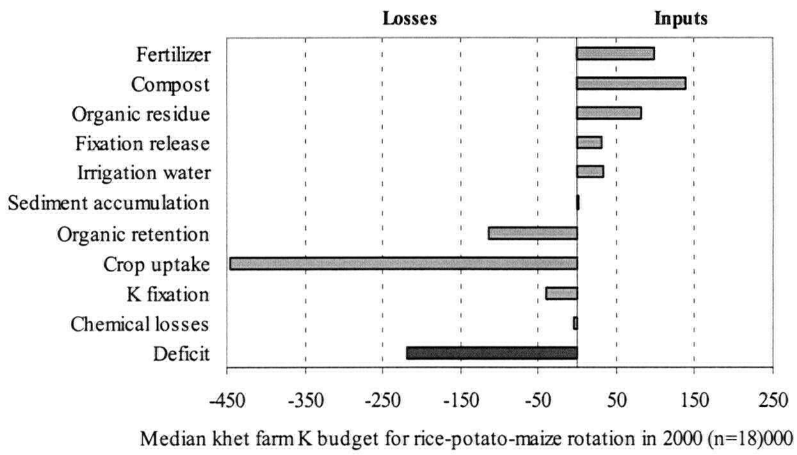


Figure 7.8 (a-f) Median khet farm nutrient budget for less-intensive (1994) and intensive (2000).

e)



f)

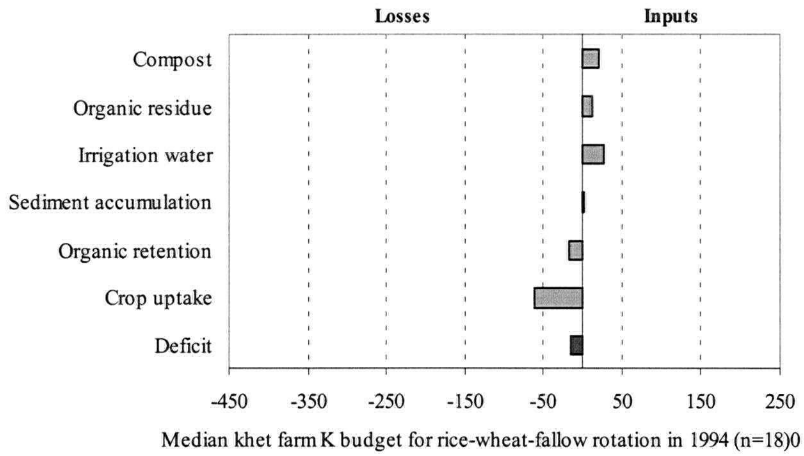


Figure 7.9 (a-f) Median khet farm nutrient budget for less-intensive (1994) and intensive (2000).

Crop N uptake increases from roughly 100 kg ha^{-1} yr^{-1} (Figure 7.8b) to almost 400 kg ha^{-1} yr^{-1} (Figure 7.8a) as a result of the increase in the number of crops grown and the change in the type of crops grown.

Median farm budgets of intensive farms have a surplus P of 127 kg/ha, a 96 kg/ha increase from the surplus of less-intensive farms (Figure 7.8c and d). This is due to the significant increase in high-P fertilizer inputs (DAP) that has occurred in intensive sites, exceeding the increase in crop uptake.

Despite increased compost use and the introduction of K fertilizer, the K deficit is greater in median intensive farms than in less-intensive farms (Figure 7.8e and f). Crop uptake of K increases from 60 kg ha^{-1} yr^{-1} in less-intensive farms to 450 kg ha^{-1} yr^{-1} in intensive farms. This is a result of the introduction of potato (see Fig 17.16c and Appendix 6) and the cultivation of three crops per year in intensive sites (2000), whereas less-intensive sites cultivate only 2 crops per year. These factors contribute to the 220 kg ha^{-1} yr^{-1} K deficit present in intensive sites in 2000. Sanchez (1976) documents comparable crop uptake values of 342 kg ha^{-1} yr^{-1} for a rice-potato-wheat rotation. The effect of the small K deficit (-14 kg ha^{-1} yr^{-1}) present in a median less-intensive farm was likely negligible, as the slow release of structural non-exchangeable K would be sufficient to buffer soil K levels and prevent a decline in exchangeable K.

7.6.3. Nutrient Budget for Dominant Khet Crops

An examination of crop specific budgets highlights the impact of changing the type of crops grown on nutrient balances (Table 7.6).

Table 7.6 Median nutrient balance of dominant khet crops. (All farmers growing the crop are considered.)

Farm system	Crop	N balance (kg ha^{-1} yr^{-1})	P balance (kg ha^{-1} yr^{-1})	K balance (kg ha^{-1} yr^{-1})
Intensive khet (2000)	Rice (n=26)	-79	+88	-51
	Potato (n=26)	+13	+19	-118
	Maize (n=18)	-8	+7	-16
Less-intensive khet (1994)	Rice (n=26)	+15	+11	-27
	Wheat (n=19)	-5	+1	+6

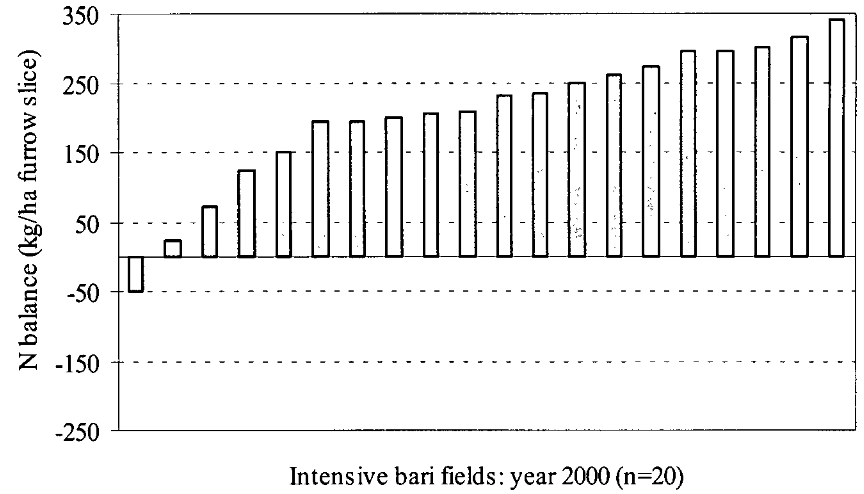
In a triple crop rotation, rice drives the overall negative N balance. Rice yields have increased with intensification resulting in greater crop uptake, however, fertilizer inputs to rice have declined, and thus a negative balance ensues. This is associated with the shift in fertilizer inputs in which the dominance of urea declines as DAP use increases. The introduction of potato has a positive benefit to the overall P balance, as potato has an annual surplus of 88 kg ha^{-1} yr^{-1}, however, potato has a disproportionately large negative impact on K budgets, although rice and maize also contribute to the overall negative balance in 2000. Under less-intensive management rice is responsible for a negative balance, however in general the nutrient budgets may be considered roughly in equilibrium due to potential modeling errors, such that small discrepancies from zero are not considered significant.

7.7. Bari Nutrient Budgets

The move towards intensive cropping rotations within bari farming systems has had positive effects on nitrogen, phosphorus, and potassium budgets. In 2000, only one farm had a negative nitrogen balance, whereas in 1994 (less-intensive) 50% of individual farms maintained a negative N balance (Figure 7.10a and c). When referring to Figure 7.10 toFigure 7.12, it is important to note that the sample size for less-intensive farms is greater (n=32) than for intensive farms (n=20). Twelve percent more less-intensive farms had negative P balances than intensive farms (Figure 7.11 a and c). A similar trend was observed for potassium, in less-intensive farms (1994) 72 % of farms had a negative K budget, while only 30% of intensive farms had a negative K budget (Figure 7.12). The positive effect on nutrient budgets under intensive management was initially surprising. This is due to several factors; first compost use has increased significantly, yet for maize and wheat crops (for which comparisons between 1994 and 2000 are possible) no significant difference in crop yield was observed. Furthermore, reported potato yields are low, significantly less than khet fields. Thus it appears that intensification has not resulted in greater yields and thus additional inputs have resulted in positive nutrient budgets.

An examination of trends between intensive sites from 1995 to 2000 shows that, with time, there is a decline in the number of farms possessing a negative balance for each nutrient and there is an increase in the maximum surplus obtained by an individual farm.

a)



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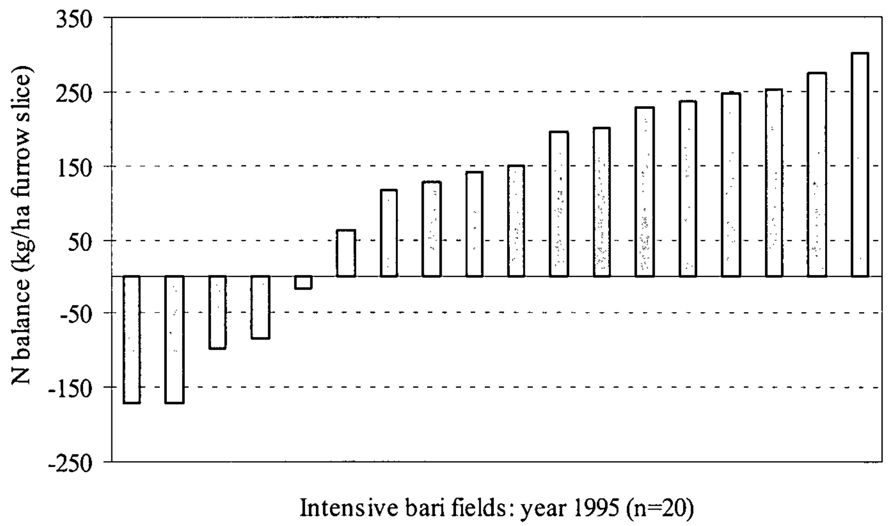

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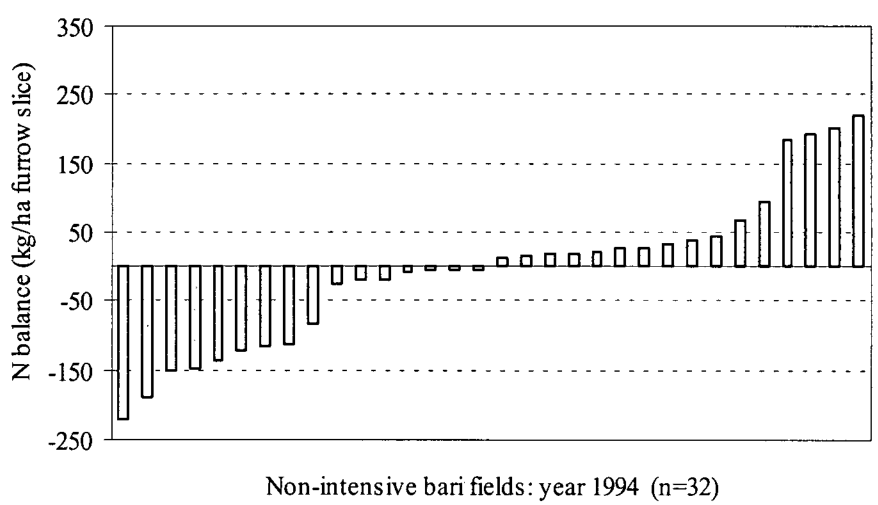


Figure 7.10 (a-c) Nitrogen budget for individual bari fields

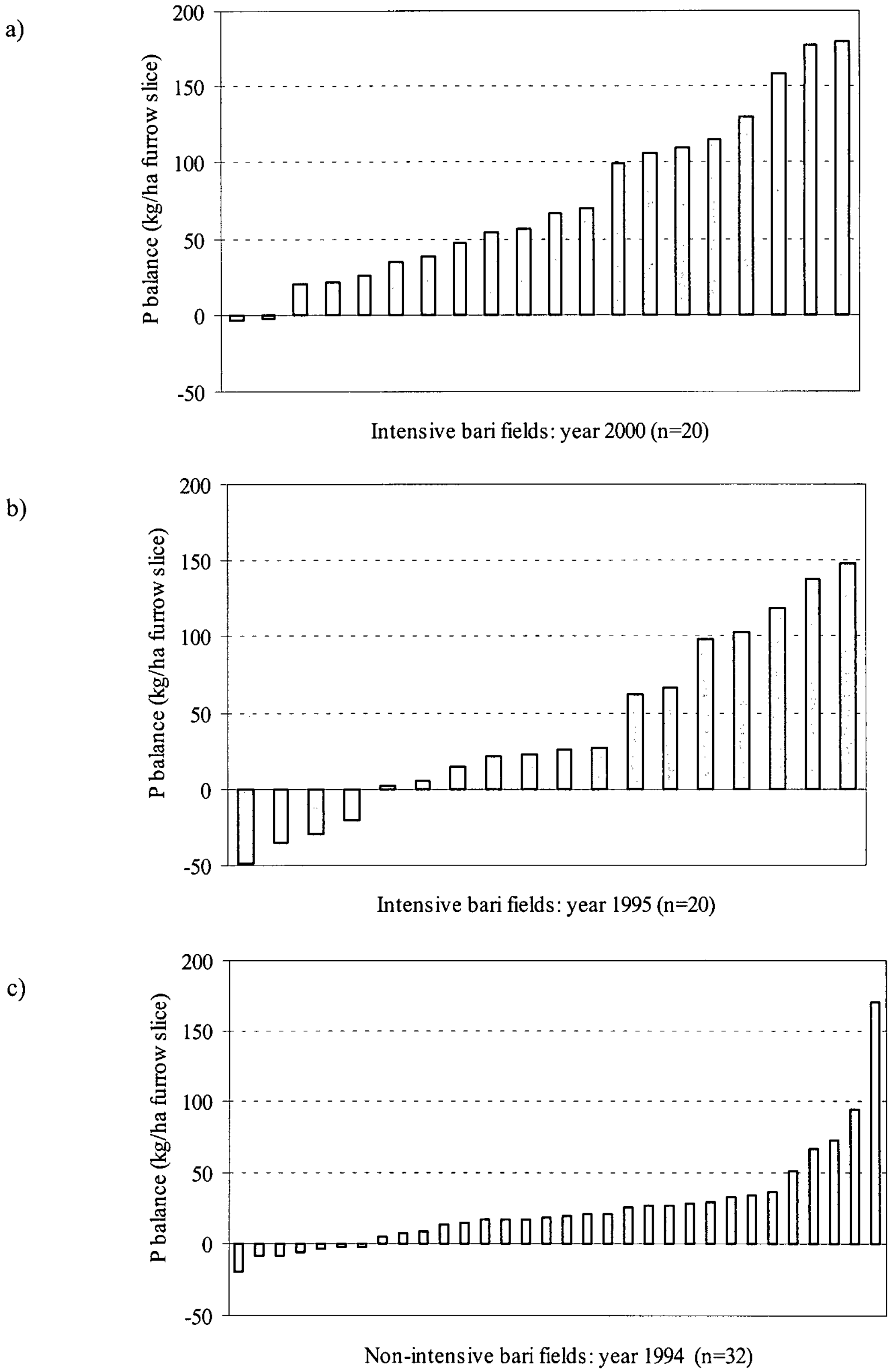


Figure 7.11 (a-c) Phosphorus budget for individual bari fields

a)

b)

c)

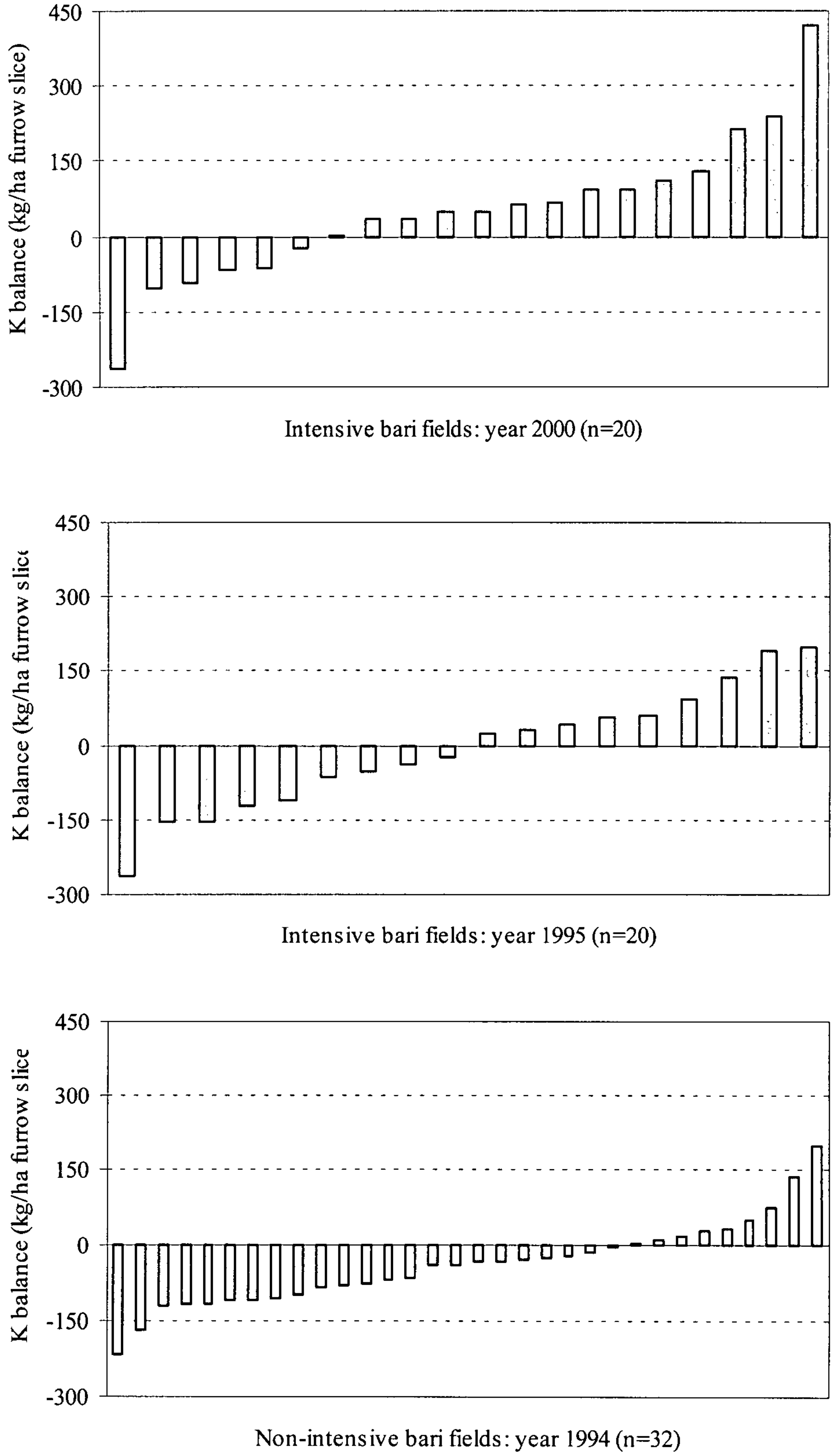


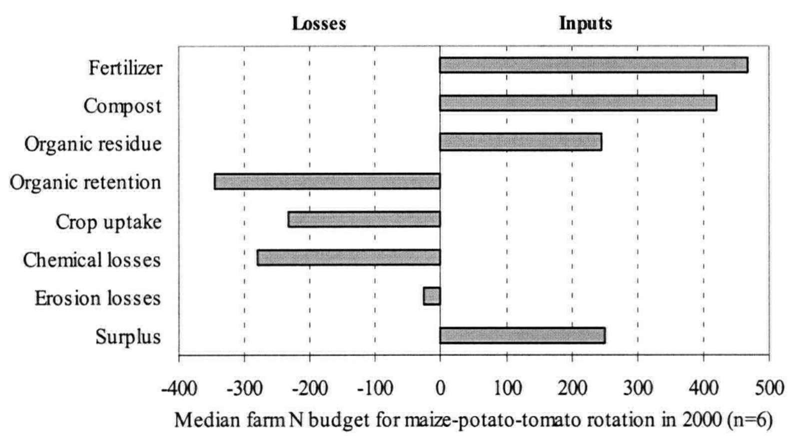
Figure 7.12 (a-c) Potassium budget for individual bari fields

7.7.1. Median budgets: based on dominant crop rotation

The dominant cropping rotation for bari fields in 2000 is a maize-potato-tomato rotation, while in 1994 it is a maize-wheat-fallow rotation. Figure 7.13 illustrates the changes in specific inputs and losses as farms shift from a maize-wheat-fallow cropping rotation to a maize-potato-tomato rotation in terms of nitrogen, phosphorus, and potassium budgets. The median nitrogen and potassium budget switches from negative in 1994 to positive in 2000 due to greater compost inputs and, in the case of nitrogen, fertilizer inputs. Phosphorus budgets go from slightly positive in 1994 to significantly positive by 2000, again due to increases in inputs comparative to crop uptake.

The small sample size (n=6) that is cultivating a maize-potato-tomato rotation may obscure potential trends. Therefore, a median farm was created by summing the individual median values for maize (n=20), potato (n=13), and tomato (n=14) (Table 7.7) to obtain an overall median. Similar trends were also observed in this hypothetical scenario.

a)



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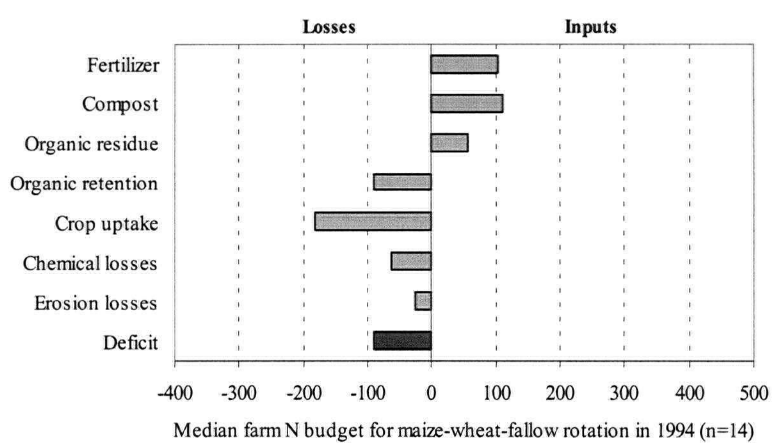

Figure 7.13 (a-f) Median bari farm budget for less-intensive (1994) and intensive (2000) sites.

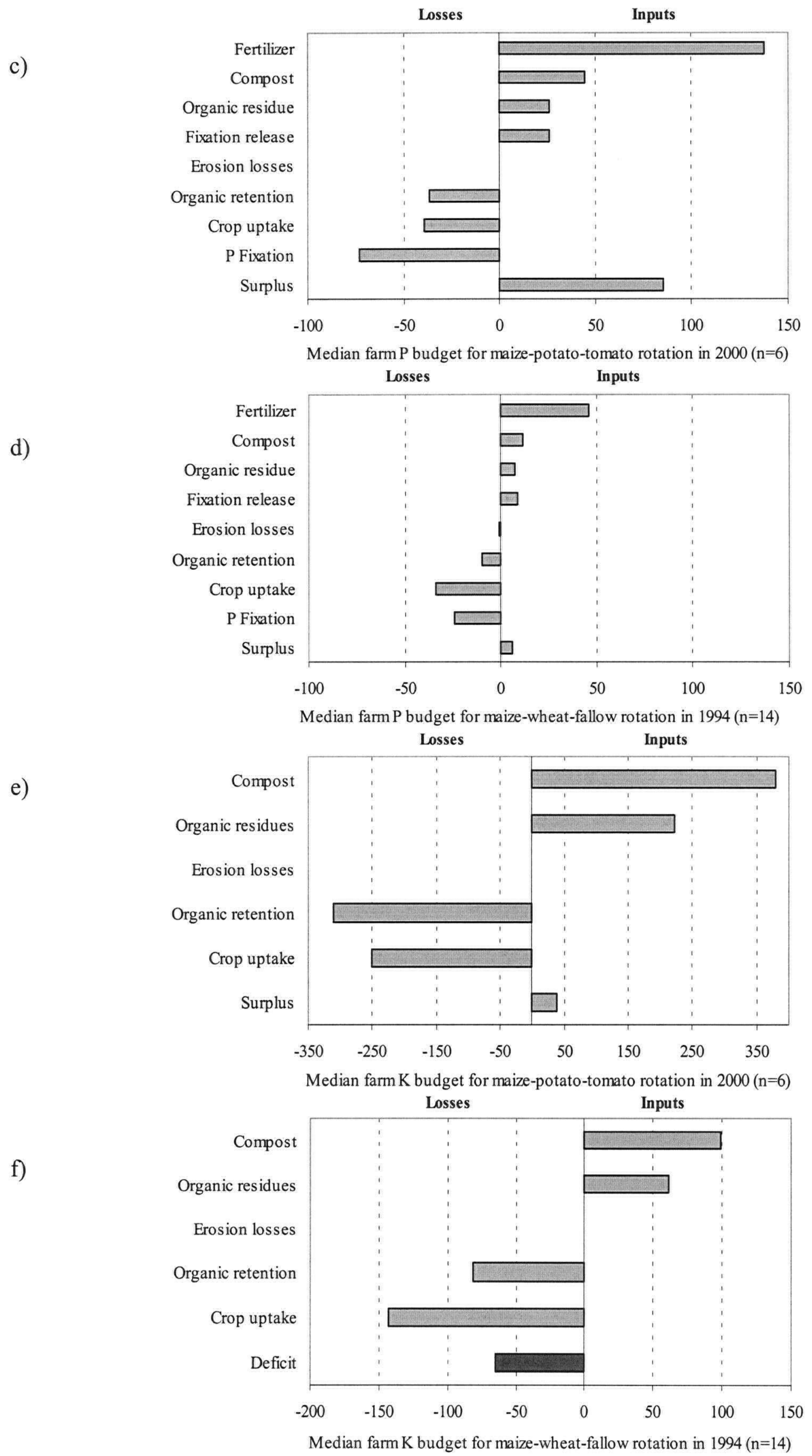

Figure 7.14 (a-f) Median bari farm budget for less-intensive (1994) and intensive (2000) sites.

7.7.2. Nutrient Budget for Dominant Bari Crops

The positive nutrient budget observed for the median farm cultivating a maize-potato-tomato rotation is being driven by the positive budgets of potato and tomato (Table 7.7). Again yields of tomato and potato are comparatively low and thus increased compost use and fertilizer use for potatoes and tomatoes exceeds crop requirements. Within less-intensive systems, the cultivation of maize causes negative nutrient balances for both nitrogen and potassium.

Table 7.7 Median nutrient budget of dominant bari crops (All farmers growing the crop are considered.)

Farming system	Crop	N budget (kg ha^{-1} yr^{-1})	P budget (kg ha^{-1} yr^{-1})	K budget (kg ha^{-1} yr^{-1})
Intensive farms (2000)	Maize (n=20)	33	2	-12
	Potato (n=13)	119	31	6
	Tomato (n=14)	116	40	61
Less-intensive farms (1994)	Maize (n=31)	-84	-3	-68
	Wheat (n=14)	10	3	9

7.8. Summary of nutrient budgets

Greater numbers of individual intensive khet farms have a negative N and K balance than less-intensive khet farms. The deficits in K budgets are substantial and although the majority of farmers are using potash fertilizer, levels are insufficient to meet the increased crop uptake by potatoes (Figure 7.15 a and b). In contrast, P inputs exceed crop uptake, resulting in all intensive farms maintaining a positive balance in 2000. This is primarily due to high inputs of DAP fertilizer.

The median farm cultivating a rice-potato-maize rotation had negative N and K budgets in contrast to the median less-intensive farm (cultivating rice-wheat) which only had slightly negative N and K budgets. The combination of rice and potato drives the increase in the budget deficit.

Fewer intensive bari farms (2000 and 1995) have a negative nutrient balance for N, P, and K than less-intensive bari (1994) farms. In addition, the value for the maximum surplus attained by an individual farm is greater under intensive farming conditions. The median farm cultivating a maize-potato-tomato rotation in 2000 maintained a positive budget for N, P, and K, while the median farm cultivating a maize-wheat rotation maintained a positive budget for P only. The positive budgets attained under intensive cropping systems are due to the significant rise in compost use combined with static yields, and thus comparatively low crop uptake of nutrients.

The surpluses in nitrogen and potassium nutrient balances that occur with intensification in bari systems are contrary to the trend in khet systems, where budgets decline. In contrast, trends within P budgets are similar for both land-use types (Figure 7.15). This is due to the high P fertilizer inputs in khet systems, which more than compensates for the increased crop uptake. For nitrogen and potassium, inputs are inadequate to meet the demands of a triple cropping rotation that incorporates potatoes and rice.

a)

b)

c)

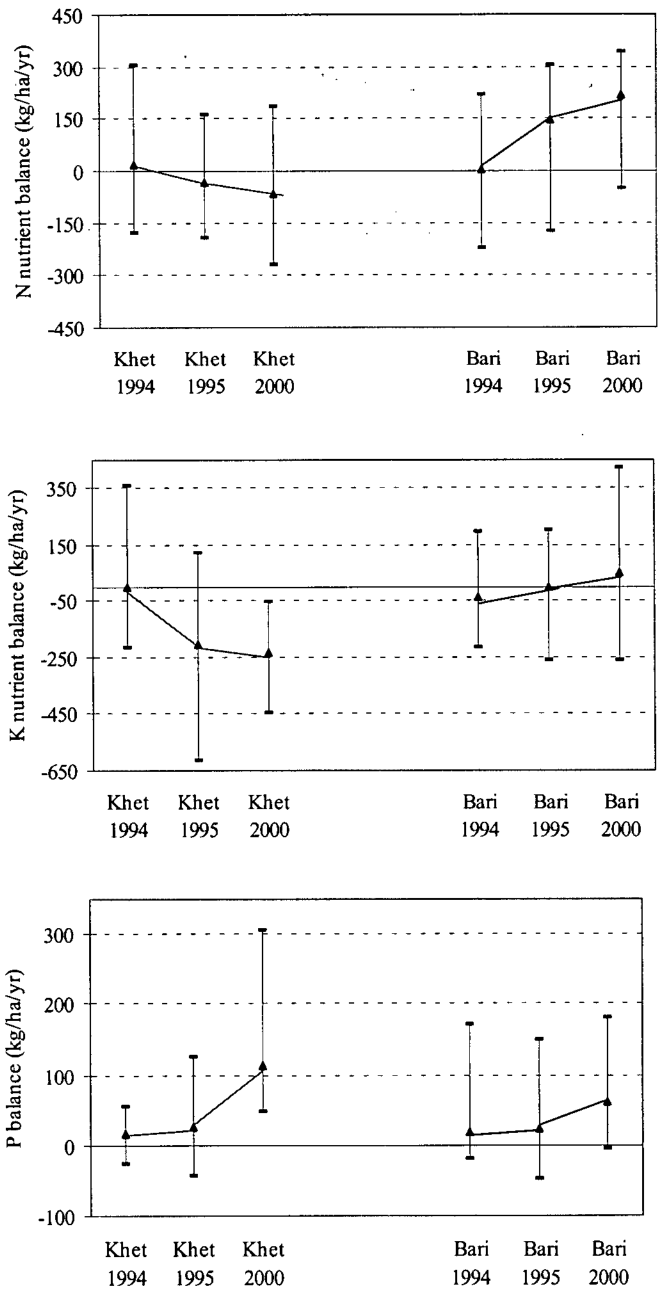

Figure 7.15 Summary of changes in soil nutrient budgets for individual fields (min, max, median).

7.9. Initial soil nutrient pool

The initial soil nutrient pool was calculated for a hectare furrow slice (15 cm soil depth by one hectare) using measured values of bulk density, nitrogen, phosphorus, and potassium (Table 7.8).

Table 7.8 Initial soil nutrient pool per hectare furrow slice for khet and bari soils

Land-use	Bulk density (kg/m^3)	Soil nutrient concentration (mg/kg) (mean values)			Soil nutrient pool (kg/ ha furrow slice)		
		N	P	K	N	P	K
Khet 2000	1170	1040	99	51	1825	174	89
Khet 1994	1170[1]	864	27	78	1516	47	137
Bari 2000	1286	780	100	156	1505	193	302
Bari 1994	1286[1]	950	29	102	1833	57	196

[1] Bulk density values were not available for 1994 samples. Therefore, based on land type, bulk density values from 2000 samples were used in calculations.

7.10. Soil fertility and directions of change

Nutrient budgets provide a valuable tool in indicating the direction of change for the nutrient in question and answering the question of whether depletion or enhancement of the soil nutrient pool is occurring. Although the release of nutrients fixed from fertilizer sources was considered, the nutrient budgets designed in this study purposely did not consider sources of inorganic N, P, and K by slow release from structural non-exchangeable sources. The contribution of these forms for both nitrogen and phosphorus is negligible as surface mineral soils have very low nitrogen and phosphorus contents and forms of phosphorus are often present as insoluble compounds. In contrast, as discussed earlier, the release of potassium from non-exchangeable structural sources of K may be considerable and may buffer levels of soil K despite a negative budget.

Figure 7.16 (a-c) illustrates the changes in nitrogen, phosphorus and potassium in the soil nutrient pool for a one year period. Under a less-intensive cropping rotation (1994 data) gains and declines in the soil nutrient pool are on a much smaller scale than under an intensive crop rotation. The soil nutrient pool approximates static/equilibrium conditions under less-intensive management for nitrogen and phosphorus. Potassium is being depleted from the soil nutrient pool under less-intensive management, but primarily by bari- maize crops.

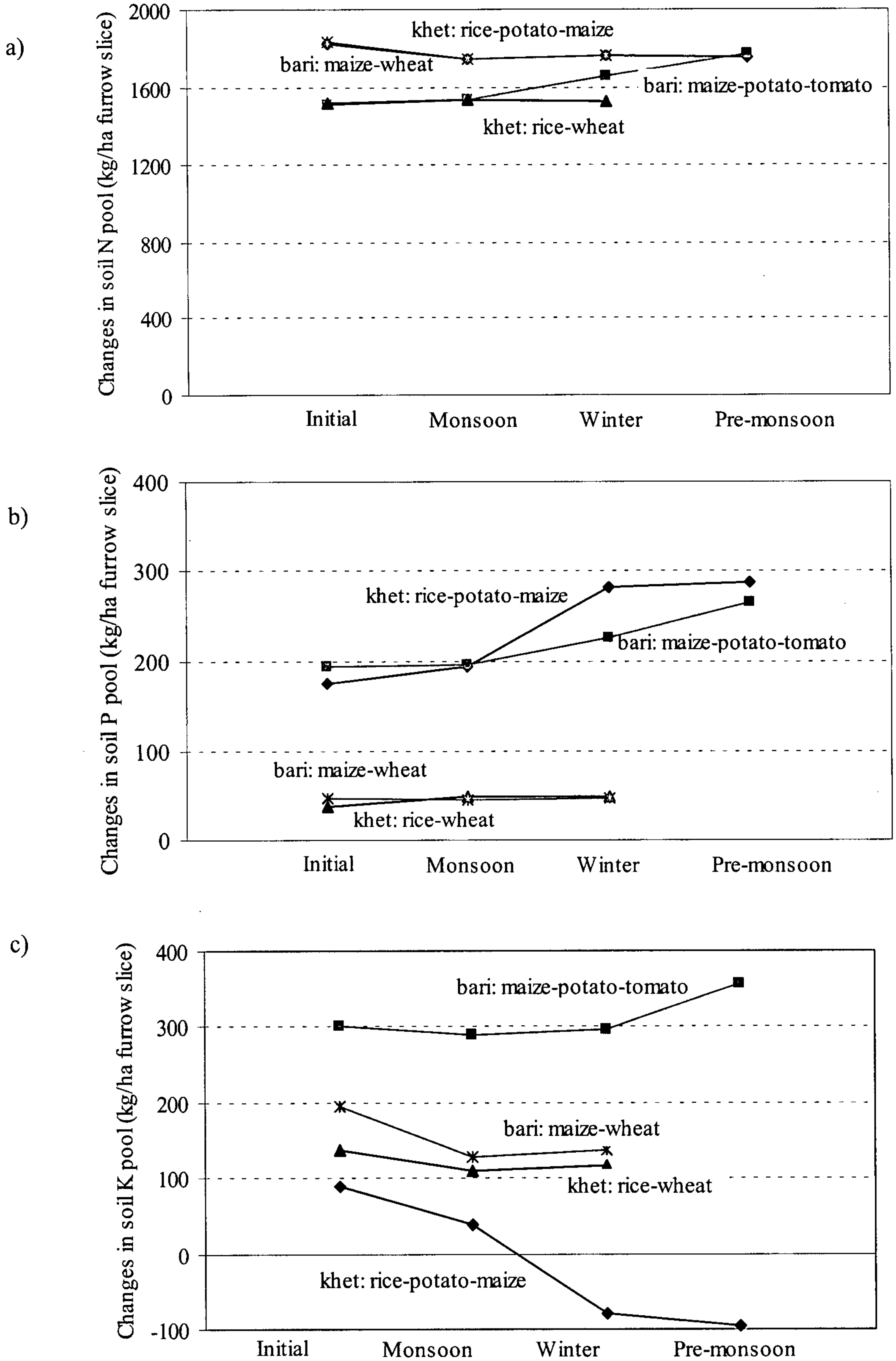

Figure 7.16 (a-c) Changes in the soil nutrient pool for nitrogen, phosphorus, and potassium

The intensive bari maize-potato-tomato rotation is enriching the soil nutrient pool. The shift to cash crops in bari has been accompanied by an increase in compost and fertilizer inputs without a corresponding increase in crop yield. Given that compost is a scarce resource it raises the question of whether other fields owned by these farmers are therefore receiving less compost inputs and experiencing declines in soil quality. In addition, it highlights the importance of compost in maintaining soil fertility in bari fields.

Phosphorus levels within the soil nutrient pool are significantly enhanced (+ 127 kg/ha) while potassium is significantly depleted (- 128 kg/ha) within intensively managed khet fields. As the depletion in potassium (primarily driven by potato) results in levels of exchangeable potassium dropping to below zero within one crop rotation it may be concluded that exchangeable potassium levels are likely at a minimal level and derived entirely from the release of non-exchangeable potassium (Figure 7.16c). To maintain potassium at current levels, non-exchangeable sources would need to contribute 120 kg/ha furrow slice per crop rotation. This is within rates of release reported by Rao and Khera (1994) indicating that exchangeable potassium is likely being supplied primarily from the release of non-exchangeable sources. Although non-exchangeable sources may continue to provide K in the future, soil levels are below desirable levels for crop production within intensive khet systems, likely limiting crop productivity.

7.11. Summary: Nutrient budgets

It is apparent that intensification and, in particular the introduction of cash crops, has impacted the nutrient budget and soil nutrient pool of khet and bari systems. In both intensive khet and bari systems gains in positive P balances have occurred, to the extent that virtually all farms in 2000 maintain a positive budget and the soil nutrient pool is being enriched. Surpluses in P are quite substantial indicating the potential for farmers to reduce P fertilizer inputs, saving money, and reducing the potential of eutrophication.

Intensified bari farms are enhancing the soil nutrient pool of nitrogen and potassium due to high compost inputs with comparatively low crop uptake. This indicates the potential for farmers to reduce compost inputs to intensive fields, so long as yields remain within the range reported. This may allow compost to be diverted to less-intensive fields positively impacting their soil fertility.

Although the dominant triple crop rotation of intensive khet sites is depleting soil nitrogen pools, of greater concern is the depletion of potassium. Depletion is of such an extent that levels of exchangeable potassium are likely derived exclusively from the release of non-exchangeable K and inputs. Although non-exchangeable sources may have the capacity to buffer K levels, on a long-time scale, without additional K inputs, farmers will continue to mine the soil nutrient pool.

8. CHANGES IN SOIL FERTILITY

The preceding discussions of input amounts and nutrient budgets are relevant when examining and explaining the differences between soil variables of:

a) intensively managed sites and control sites and,
b) khet and bari sites
c) between intensively managed sites (2000 only) and less-intensively managed sites (1994).

This information provides an understanding of how soil properties may be changing under intensified conditions, whether relationships between inputs and soil properties are apparent, and whether soil acidification is occurring.

Soil samples were available from intensive sites and control sites sampled in 2000, as well as from less-intensive sites sampled in 1994. Thus, all references to "intensive sites" or "control sites" refer to soil samples collected in 2000, while all references to "less-intensive sites" refer to soil samples collected in 1994.

8.1. pH

A major concern relating to intensification has been that the use of greater fertilizer inputs will result in soil acidification. Under less-intensive management, khet soils have been documented to have a higher pH than bari, presumably due to Ca inputs in irrigation water (Schreier *et al.* 1994, Wymann 1991, Vaidya *et al.* 1995). The pH of khet control sites was significantly higher than bari control sites (Figure 8.1a) as was the pH of less-intensive khet compared to less-intensive bari sites (Figure 8.2a). These results concur favourably with those of literature sources. In contrast, the pH of intensive khet was not significantly different from intensive bari sites sampled in 2000. This may be due to an increased compost input to intensive bari site and increased fertilizer inputs to intensive khet sites, resulting in a slight decline in the pH of khet sites and a slight increase in the pH of bari sites. However, within a specific land-use type, no significant difference in pH was observed between intensive and less-intensive conditions (Figure 8.2a).

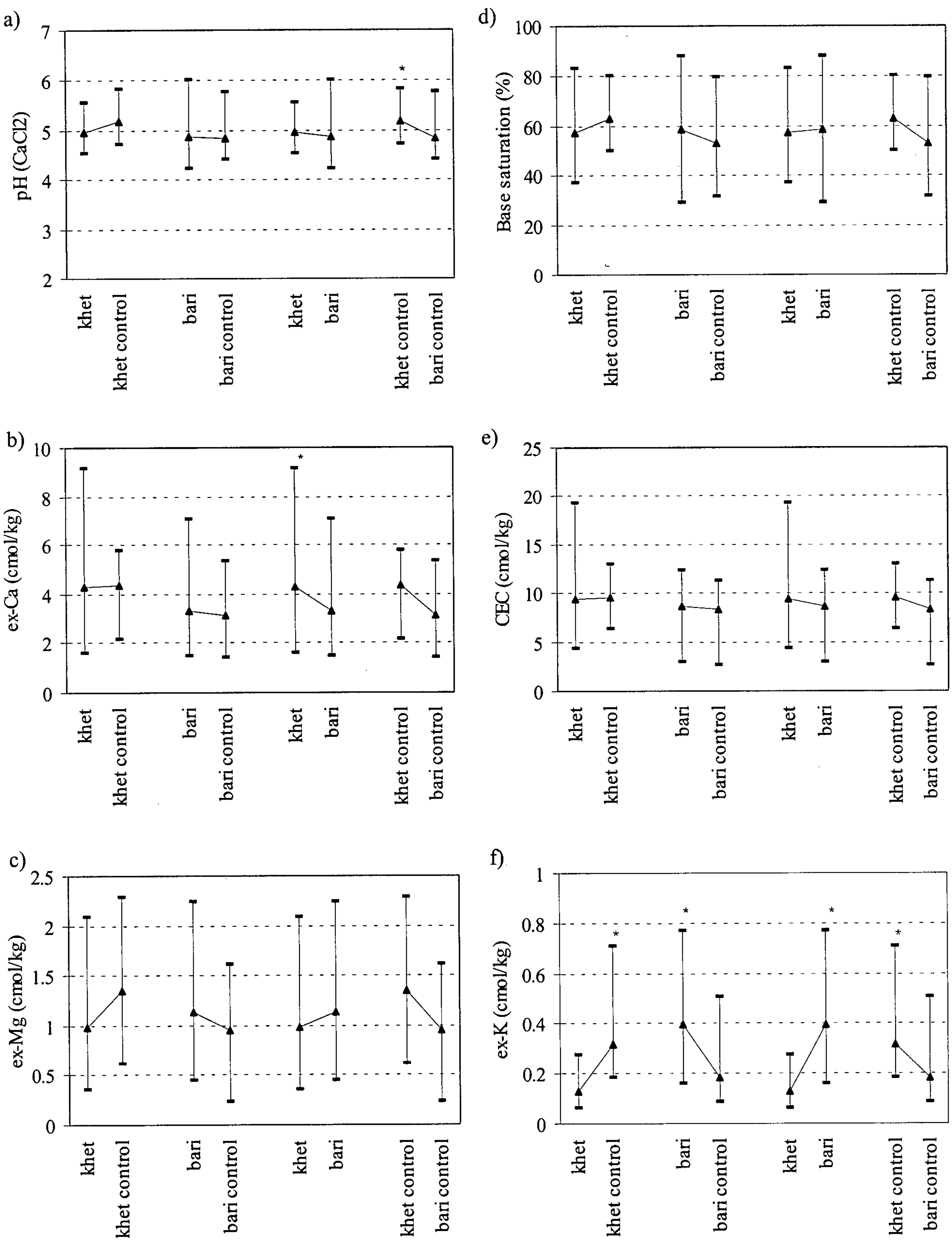

Figure 8.1 (a-i) Differences in soil fertility between groups (Mann-Whitney-U); minimum, maximum, and mean (▲). (khet n=26, bari n=23, khet control n=9, bari control n=11).

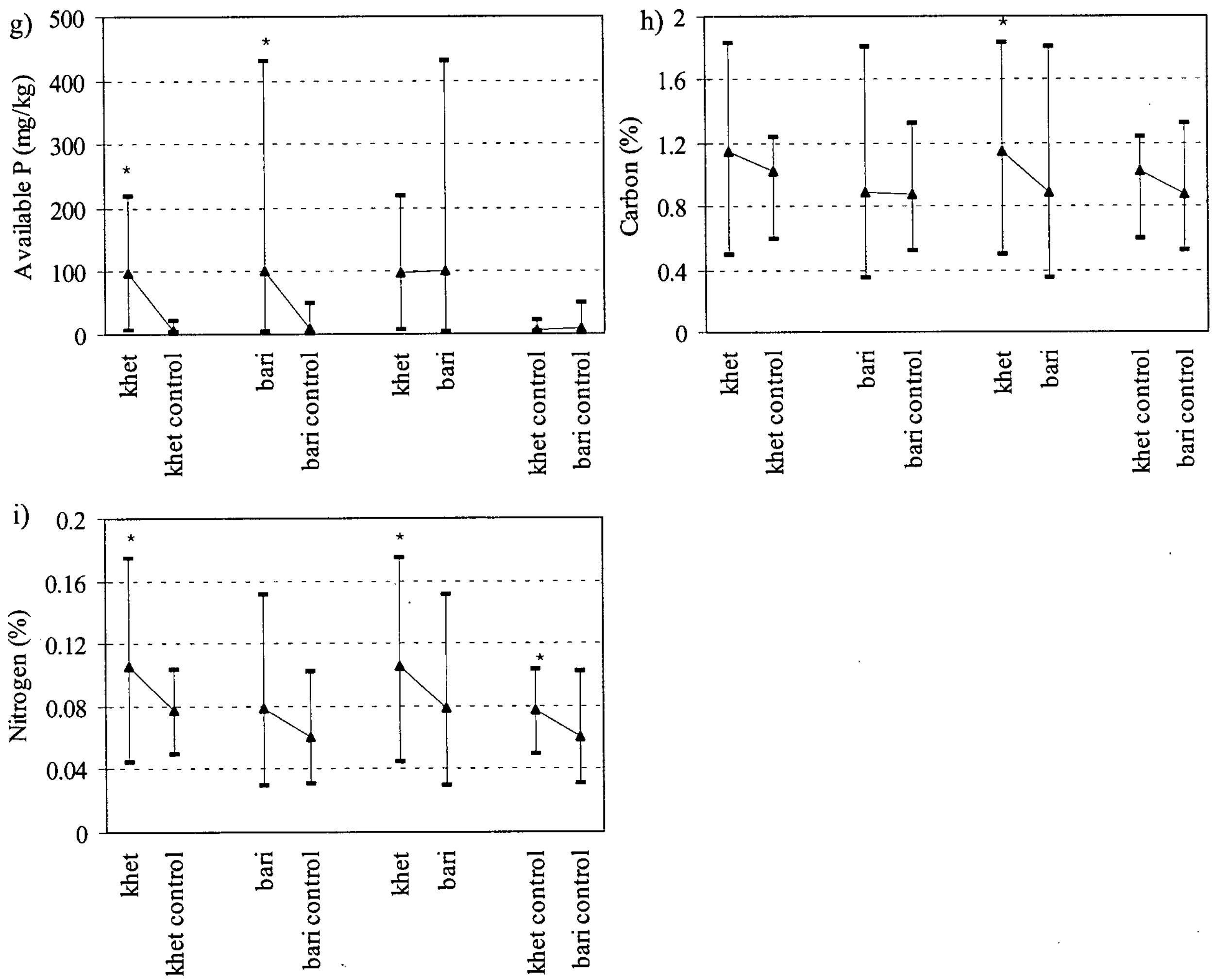

Figure 8. 1 (a-i) Differences in soil fertility between groups (Mann-Whitney-U); minimum, maximum, and mean (▲). (khet n=26, bari n=23, khet control n=9, bari control n=11).

Thus, when pH is used as an indicator, intensification has not resulted in any appreciable soil acidification. This is likely the result of the buffering effect of soil aluminum, which will maintain the soil pH at ~ 5.0 despite acidic inputs. The lack of acidification within intensive khet sites, despite increased fertilizer inputs, may also indicate that additional compost inputs (primarily due to potato cultivation) and/or increased calcium through additional irrigation in intensive khet sites are buffering the effects of soil acidity. Alternatively, the time-span (6 years) may be insufficient to observe potential acidification due to increased fertilizer use, particularly as the soils are already strongly acidic and thus may require significant levels of acidic inputs to further cause declines in pH.

Soil correlations (Section 4.2) indicated that CEC was positively correlated with organic matter content. CEC derived from organic matter is pH dependent and thus, it is expected that differences in CEC will mimic those observed for pH. This was valid for all comparisons (Figure 8.1a and Figure 8.1e).

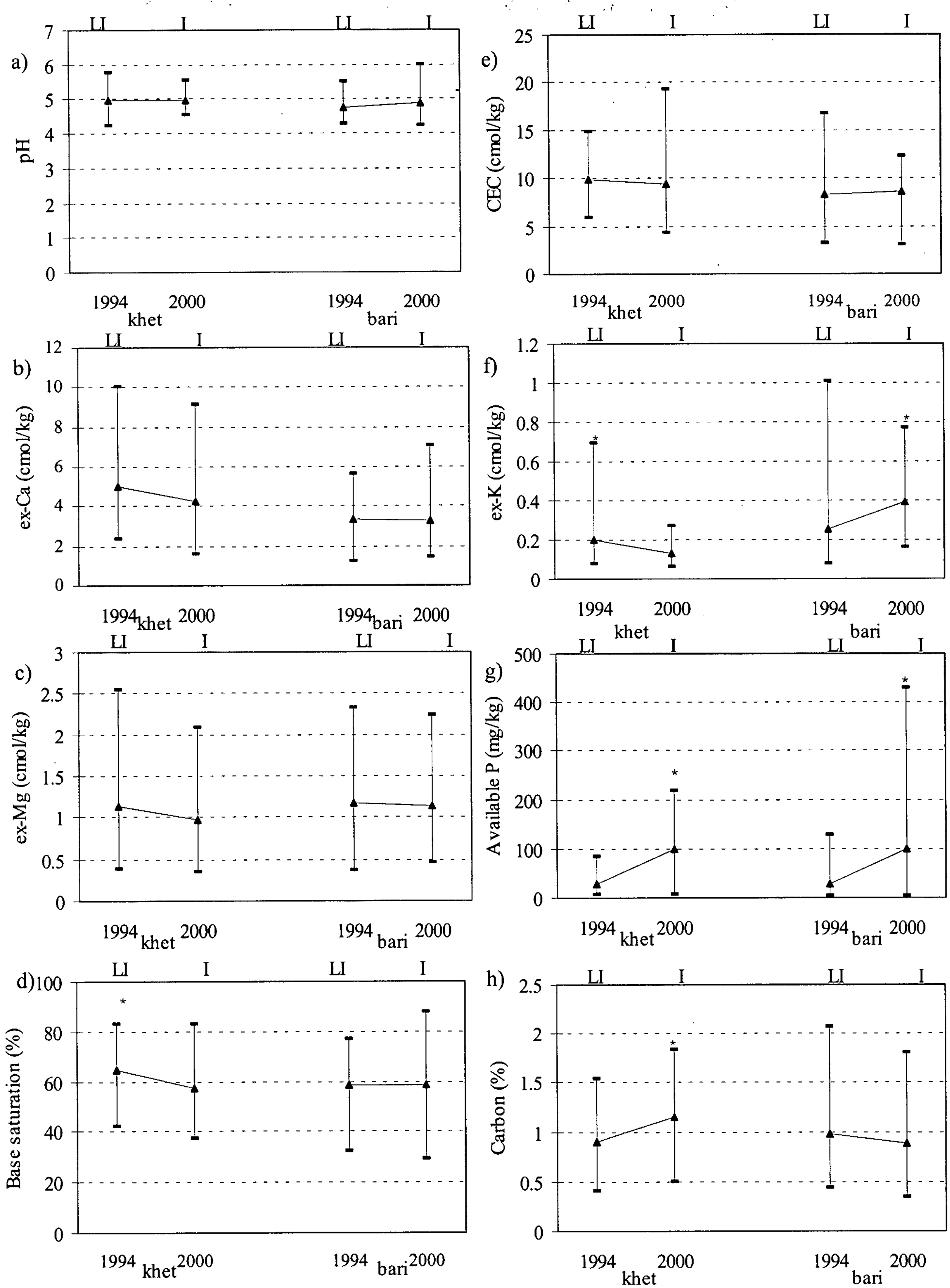

Figure 8.2 Differences in soil variables between intensive (I) (2000) and less-intensive (LI) (1994) sites.

8.2. Calcium, magnesium, % base saturation and cation exchange capacity

The levels of exchangeable calcium for control sites did not differ significantly from their respective intensive khet or bari counterpart. In contrast, levels of exchangeable Ca in khet sites were significantly greater than bari sites for both intensive (Figure 8.1b) and less-intensive sites (Figure 8.2b). These differences between land use groups agree with the expected result, as khet lands receive higher calcium inputs due to irrigation inputs.

Calcium levels in intensive khet sites are significantly less (α <0.10) than in less-intensive khet sites, despite an additional 70 kg ha^{-1} yr^{-1} of Ca from irrigation water inputs to the potato crop. This may indicate that calcium is buffering acidic inputs from increased fertilizer use.

No significant difference was observed in magnesium levels either between land-use and control sites, between land-use groups (Figure 8.1c), and between less-intensive versus intensive farming systems (Figure 8.2c). However, although statistically insignificant, intensive farming systems have lower mean soil Mg levels than less-intensive systems (Figure 8.2c).

Previous research findings indicate that typically percent base saturation is greater in khet than in bari soils. Less-intensive sites followed this trend with a significantly greater % base saturation in less-intensive khet sites than in less-intensive bari sites (Figure 8.2d). However, no significant difference was present in the % base saturation between intensive khet and bari sites (Figure 8.1d). Furthermore, intensive khet sites had significantly lower levels of % base saturation than less-intensive khet sites (Figure 8.2d). No significant differences were observed in % base saturation when comparing intensive khet versus khet control sites, intensive bari versus bari control sites (Figure 8.1d), nor between intensive bari versus less-intensive bari sites (Figure 8.2d). This again indicates that basicity in intensive khet sites has declined from 'typical' levels, most likely due to increased acid-generating inputs.

Levels of calcium, magnesium, and percent base saturation may all be used as alternative indicators of acidity. Levels of calcium and percent base saturation are significantly less in intensive khet sites than in less-intensive khet sites, while exchangeable magnesium shows lower levels, albeit this is statistically insignificant. The concurrence in the trends of these three indicators suggests that conditions have become more acidic in intensive khet sites.

In contrast, intensive bari, which has significantly greater compost additions and significantly less fertilizer inputs than intensive khet sites, do not exhibit significantly reduced levels of calcium, magnesium or percent base saturation than less-intensive bari sites. It appears that although intensification has not directly impacted pH in intensive khet sites, it has affected the retention of cations within the soil, which may be acting as an early warning of acidification processes within intensive khet sites.

8.3. Potassium

Potassium is unlike any of the other cations examined as significant differences were observed for all comparisons. Intensive khet sites have significantly lower levels of exchangeable potassium than khet control sites, intensive bari sites (Figure 8.1f) and less-intensive khet sites (Figure 8.2f). In contrast, intensive bari sites have significantly higher levels of exchangeable potassium than both control sites (Figure 8.1f) and less-intensive bari sites (Figure 8.2f). These results match the processes documented by the nutrient budgets in which potassium is being depleted from the soil nutrient pool in intensive khet farms and being enriched in intensive bari farms.

The drop in soil potassium with intensification is not a process unique to the Jhikhu Khola watershed. Jian-Chang and Hasegawa (1985) reported the development of serious K deficiency in large areas in southern parts of the People Republic of China due to intensified cropping practices, including the increased use of N and P fertilizers. A five-fold increase in potassium removal by crops was documented to have occurred in the Hunan Province between 1953 and 1978. Similarly, triple cropping south of the Yangtze River enhanced the rapid depletion of soil K. Tandon and Sekhon (1988) estimated crop removal of potassium by crops in India to be 10-12 times the quantities added through fertilizers and 2.5 times the quantities added when organic sources and fertilizer inputs are considered. Thus, most Indian States had negative K-balances resulting in depletion of soil K. Pretty and Stangel (1985), in a review of global trends of potassium use, also comment that increased use of fertilizer and production inputs can quickly shift soils considered adequate in K to a deficient state.

The significant drop in potassium levels in intensive khet sites also indicates that the release of non-exchangeable potassium is insufficient to buffer soils and that depletion of soil K is occurring. The management of potassium, through additional compost inputs or potash inputs, is critical in intensively cropped khet sites that incorporate potato into their crop rotation. The positive correlation between potato yield and potash inputs indicates that the low soil K levels in khet farms detrimentally affects crop yield. Deficits in K may also lead to a diminution in crop yield response to N inputs, further reinforcing the need to focus attention on K balances.

8.4. Phosphorus, carbon, and nitrogen

Intensive khet and bari sites have significantly higher levels of available P than their corresponding control sites (Figure 8.1h) and less-intensive sites (Figure 8.2h). It is evident that the combination of significantly increasing DAP inputs and compost inputs has more than surpassed plant uptake and has impacted the levels of available P. In light of these high levels of available P, farmers could likely reduce fertilizer inputs without impacting crop yield. Phosphorus has previously been considered a limiting nutrient to agriculture, and the increase of available P to levels above what is considered desirable for crop production is a positive development. However, a caveat is that runoff and leaching of excess P into surface and ground waters can lead to eutrophication. In addition, excess available P can, in certain instances, reduce crop yield (e.g. heavy applications of P may depress tomato yield (Adams 1986)). Thus levels of P inputs should be within a range where neither available P is neither limited nor in excess.

Soil carbon and nitrogen in intensive khet sites is significantly greater than in intensive bari sites (Figure 8.1h and Figure 8.1i). Soil nitrogen in intensive khet sites was also significantly greater than levels for khet control sites. In contrast to these findings, Schreier *et al.* (1994) determined that percent carbon and nitrogen was greater in bari than in khet soils. Similarly, less-intensive bari sites had higher levels of carbon (though not statistically significant) than less-intensive khet sites. Based on the absolute amount of compost inputs it was expected that percent carbon and nitrogen would also be greater in intensive bari than in intensive khet sites. The significant increase in the % C in intensive khet sites only is likely as a result of intensive khet sites receiving more compost inputs than in the past, in combination with slower rates of organic matter decomposition in intensive khet sites. The slower decomposition rates are due to the frequent flooding of khet fields, which results in a greater accumulation of soil C and N than occurs in bari systems. Intensive khet sites thus had significantly higher levels of % soil C than less-intensive sites (Figure 8.2h). Despite this increase, it is important to remember that soil C and soil N still remain below desirable levels for crop production.

8.5. Summary: Soil fertility dynamics

A comparison of soil variables of intensively managed sites with those of control sites and those of less-intensively managed sites, concurrent with a knowledge of inputs provides an understanding of the soil fertility status of intensively managed sites.

Levels of exchangeable Ca, Mg, and % base saturation in intensive khet sites are all less than less-intensive khet sites. This indicates that conditions are more acidic within intensive khet sites, likely due to increased fertilizer use. Soils are already strongly acidic and further declines in base cations may detrimentally affect gains in crop yields. Changes in soil basicity did not significantly affect pH within intensive khet sites. The data in this study does not support the notion that acidification is occurring in intensive bari sites despite increased fertilizer inputs. The large amounts of compost inputs may be buffering changes in soil acidity in intensive bari sites.

Carbon and nitrogen levels within intensive khet sites are significantly greater than their bari counterparts. This is contrary to conventional patterns, in which bari soils typically are higher in carbon and nitrogen. This may be due to increased compost additions to intensive khet sites combined with slower decomposition rates due to frequent flooding, thus resulting in increased accumulation of soil C and N within khet soils. Soils in both land-types are still below desirable levels of soil carbon and nitrogen for crop production.

The two most significant results of this study, in terms of changes in soil fertility, have been the unexpected finding that levels of soil potassium have significantly dropped within intensive khet sites and the dramatic increases in available P in intensive khet and bari sites. Declines in soil K match the negative K balances related to potato production observed in intensive khet sites. Increases in available P are linked to the high P surpluses in nutrient balances driven by government policy and its influence on DAP inputs for both khet and bari sites.

9. SUMMARY AND CONCLUSIONS: AGRICULTURAL INTENSIFICATION

The effects of agricultural intensification and the subsequent increase in the number of crops grown per annum has raised fears that inputs are insufficient to meet increases in crop uptake, that farmers are diverting compost to intensive fields, that increased dependence on chemical fertilizers is causing soil acidification, and that generally intensification is associated with declines in soil fertility. This study examined these issues within the Jhikhu Khola through soil samples, questionnaires, and nutrient budgets. Soil samples as well as information on crop yield and inputs were collected from 26 intensive khet fields and 20 intensive bari fields to provide a picture of conditions under intensive agriculture in 2000. Yield and input data for 1995 was also collected in the 2000 survey for these sites. A comparison to less-intensive conditions was possible by access to data collected by Brown (1997) of soil conditions and inputs in 1994 to farms within a similar area.

Farmers have significantly increased total fertilizer inputs between 1995 and 2000 in both intensive khet and bari sites. The increase in fertilizer use within intensive khet sites is primarily due to increased applications of diammonium phosphate (DAP) to potatoes. Urea inputs to maize and potato crops increased slightly. Within intensive bari sites trends in urea and DAP use between 1995 and 2000 varied by crop. Urea applications to tomato declined, while DAP inputs increased. Inputs of urea and DAP to maize increased, while inputs to potato were the same in both years. The overall increase in DAP is related to the increased cultivation of tomato and potato, a policy decision by the AIC to sell DAP instead of the fertilizer Complex, and the removal of fertilizer subsidies reducing the price incentive to use urea. An additional aspect of intensification within intensive khet fields has been the 76% increase in the use of potash for potatoes.

Compost inputs to both intensive khet and bari fields were not significantly different between 1995 and 2000. Farmers of intensive fields are increasingly using fertilizers between 1995 and 2000 to meet perceived nutrient needs. Since compost is in limited supply the relatively constant rates of compost inputs may be due to the inability to acquire more compost inputs or an unwillingness to divert supplies from other fields.

Intensive farms utilize significantly more fertilizer and compost than less-intensive farms. The increased use of compost in intensive sites to that used in less-intensive sites suggests that farmers are diverting compost from other fields, as it is unlikely that compost supplies have significantly increased within the study area (Brown 2001, pers. comm.)

Nutrient budgets for nitrogen, phosphorus, and potassium were calculated to determine whether inputs were sufficient to meet crop uptake. Nitrogen and potassium inputs are inadequate on a median intensive khet farm, resulting in a deficit situation. A greater number of individual intensive khet farms have negative nitrogen and potassium balances (of higher magnitude) than less-intensive farms. Budgets were calculated for each individual site as well as for a median farm. In contrast, considerable surpluses exist in the P balance of intensive khet farms. To attain nutrient balances closer to equilibrium intensive khet farmers could decrease P inputs and increase N inputs to rice, while considerably increasing inputs of K to potatoes and rice.

Nutrient balances for intensive bari sites indicate an increase in nitrogen, phosphorus, and potassium budget surpluses between 1995 and 2000 and between less-intensive and intensive sites. Farmers within intensive sites have increased fertilizers inputs, in addition to increasing compost inputs from levels present in less-intensive sites, yet no corresponding increase in yield has occurred. As a result, the increase in nutrients supplied exceeds crop uptake. Until gains in crop yield occur, the majority of farmers within intensive bari fields can reduce inputs without depleting the soil nutrient pool.

The soil fertility of the intensive sites sampled are similar to previous studies of soil fertility in many aspects. Soils are strongly acidic, and levels of % C, % N, CEC, and Mg and K base cations are all low. Intensive sites are, however, atypical in that available P levels are high. This is related to high P inputs and a 26% increase in the P content of the dominant fertilizer used. This has resulted in surplus P balances and has lead to an accumulation of soil P. This is significant as available P was previously a limiting nutrient in the Jhikhu Khola watershed. Levels of P exceed minimum requirements desirable for crop production, with subsequent enrichment of the soil nutrient pool. In contrast, potassium, previously ignored in many studies due to assumptions of adequacy, has been depleted within intensive khet farms. This is due to inadequate compost and potash inputs and the high K demand of potatoes. Soil K is critically low, and levels of exchangeable potassium are likely entirely due to the release of non-exchangeable K. Further depletions of the soil nutrient pool will likely negatively impact crop yields and depress yield response to other fertilizer inputs.

The greater dependence upon chemical fertilizers to meet nutrient needs has not affected the pH of intensive bari or khet farms, however intensive khet sites have lower levels of exchangeable Ca, Mg, and % base saturation than less-intensive khet sites. Thus, although intensification is not linked to acidification using pH as an indicator, it is linked to declines in base cations for intensive khet sites. This likely indicates that acidification is occurring to some degree. Further declines in base cations may detrimentally impact crop yields.

9.1. Experimental improvements

All attempts were made to minimize error including a composite sampling approach, surveys written and conducted in Nepali, and duplicate laboratory analysis for 10% of the samples. However, the design of the questions, interviewer bias, and the reliability of farmer responses, which could not be independently assessed, may have introduced error into the survey data. Improvements to the experimental design include:

1) A larger sample size. Although this would likely be difficult for intensive bari sites, it is quite feasible for intensive khet sites and would increase the power of the results.
2) Sampling the nutrient content of compost from a sub-sample of the individual fields would increase the reliability of nutrient budgets.
3) Questions in the survey (Appendix 1) on how farmers transport compost to their fields, the distance they transport compost to the field, what limits their use of compost, and whether they diverge compost from their less-intensive fields to their intensive fields.
4) Independent verification of yield data, particularly for intensive bari sites, where reported crop yields were low given the level of inputs.

This study provides an understanding of the shifts occurring in a typical Middle-Mountain watershed as farmers move from less-intensive to intensive cropping practice to meet greater food demands arising from population growth. It indicates that management strategies towards maintaining soil potassium need to become a priority; in addition careful monitoring of base cations is needed to ensure that acidification is not occurring in intensive khet lands or that imbalances among Ca/Mg or Ca,Mg/K ratios do not occur. Furthermore, it indicates that P inputs may be reduced, assuming crop demands remain the same. This will prevent water eutrophication and an unnecessary economic expenditure by farmers. An examination of soil physical properties would also provide additional information about soil fertility; however, due to the large in-field variation of physical variables and the time-consuming nature of assessing soil physical properties this was not done in this study.

10. IRRIGATION AND FOOD PRODUCTION

10.1. Introduction

Soil fertility is one important aspect towards increasing food security and food productivity. Equally important is irrigation. Irrigation has played a fundamental role in food production both historically and in modern agriculture. Worldwide, irrigated cropland comprises only 18% of available cropland, yet it produces 33 % to 40% of the world's food (FAO 1997, Gleick 2000). Large increases in land productivity in the 1960's and 1970's occurred due to the rapid (> 2 %) rate of expansion of irrigated areas along with the introduction of high yielding varieties and chemical fertilizers (Postel 2000). In Asia, 70% percent of all additional food grain production since the beginning of the Green Revolution has been on irrigated land (Seckler 1994). Irrigation improves the stability and predictability of water supplies, which promotes better crop planning and provides the opportunity for multiple cropping and higher yields. Thus, irrigation is key to realizing the predicted need to double the world's food production by the year 2020 to meet the increased food demands due to population increase and changing dietary habits (FAO 1997).

Currently, irrigated agriculture consumes ~ 80 % of the worlds developed water supplies (this excludes water used by rainfed agriculture) with surface irrigation as the dominant irrigation method in most regions of the world (FAO 2000c). Surface irrigation, in which water is applied to the edge or at a point of the field and spreads by gravity and hydrostatic pressure, includes basin, furrow, and border irrigation methods (Heermann *et al.* 1990). The prevalence of this irrigation method is due both to the low capital costs and the low required technical knowledge associated with its use. The disadvantage of surface irrigation is that typical application efficiencies are low (40-70 %) (Sivanappan 1995, Postel 2000) and often even less in larger systems in developing countries (project efficiencies of only 25-35 %), due to a variety of factors such as poor planning and design, inadequate system maintenance, and poor system management (Figure 10.1). However, given recent trends of declining rates of expansion of irrigated areas as the cost to develop suitable land and water resources increases (FAO 1997) and as the demand for water from industrial, domestic, and environmental sectors increases, it is unlikely that surface irrigation will be able to expand. These factors are even more pronounced in developing countries with high rates of population growth and urbanization (Seckler 1994).

Agriculture is thus faced with the need to increase food production to meet future global needs while facing the challenges of increasing per-capita water demand, declining per capita water availability, and

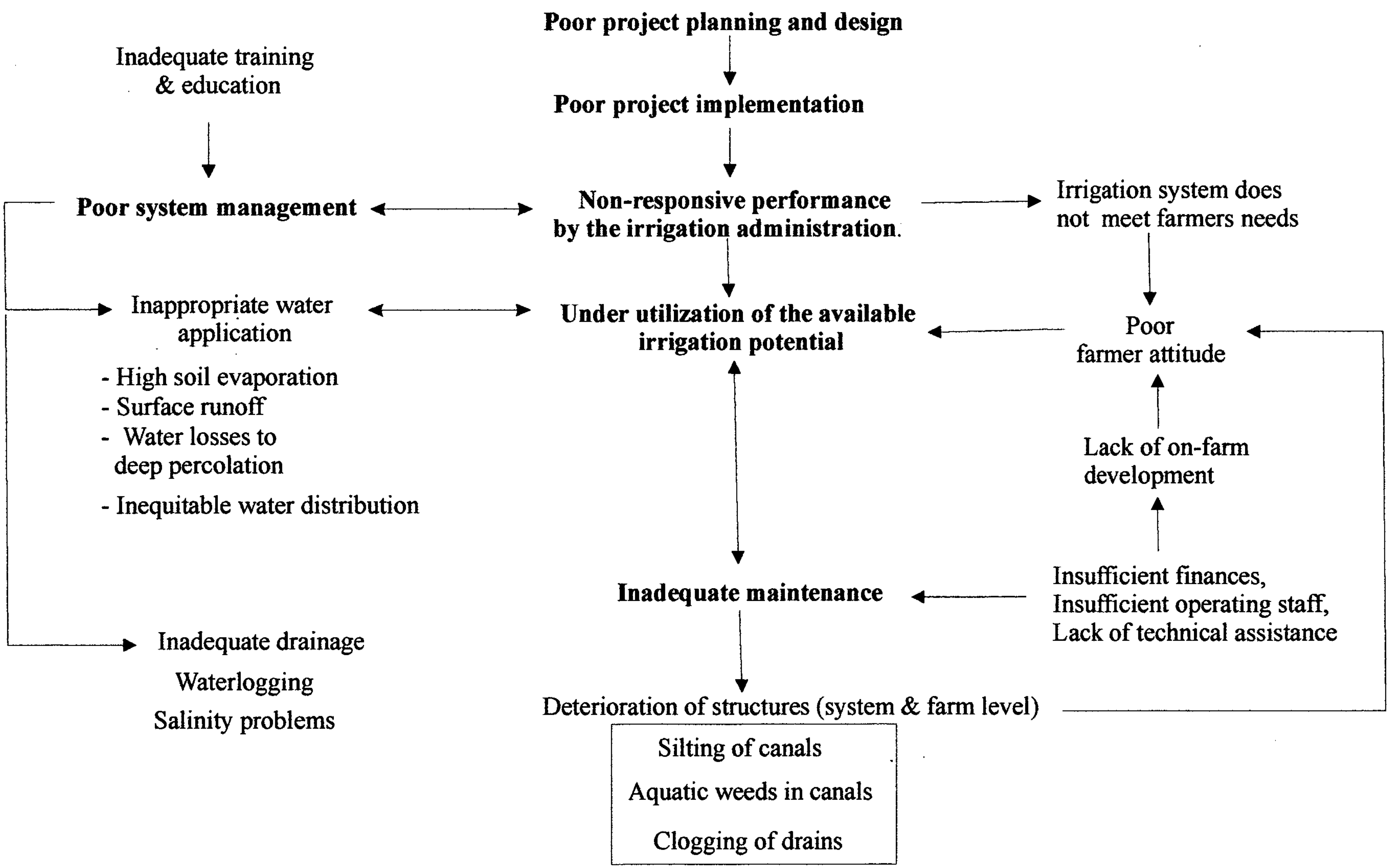

Fig. 10.1 Typical causes and effects of poor performance of irrigation systems within developing projects (based on Easter 1993, Howe & Dixon 1993, & FAO 1997).

declining amounts of irrigated land per capita. To meet these goals agriculture water use must become more efficient and provide irrigation methods accessible to the majority of the world's farmers.

Surface irrigation is utilized for ~ 98% of the world's irrigated lands yet its field-level application efficiency[1] is only 40-50%. By shifting to irrigation methods such as sprinkler or drip irrigation with application efficiencies of up to 70 to 90 %, large savings in water use are possible at the field-level scale, assuming systems are competently managed (Postel 2000, Heermann *et al.* 1990). As water is applied more effectively, farmers can utilize a smaller amount of water to irrigate a crop. This is of considerable importance to the many farmers who have limited access to water due to a lack of infrastructure and/or climatic considerations. However, until recently both sprinkler irrigation and drip irrigation technology has been limited primarily to developed countries due to cost and technical considerations. This is changing with the development of low cost drip irrigation, which offers a means for farmers in developing countries to utilize small sources of water to grow an additional crop, enhancing both their economic and food security. The ability to expand drip irrigation and/or sprinkler irrigation to developing countries will be a significant step towards improving agricultural water use and meeting future food demands.

This study was conducted to examine and quantify the performance of low cost drip irrigation in a field setting in Nepal and to compare it with application of water by hand and by a Western drip irrigation system.

10.2. Drip irrigation

In drip irrigation, water is dripped to the plant root zone at low rates (2-20 L/hr) from emitters embedded in small diameter plastic pipes. Systems may be surface or subsurface. Drip irrigation typically has high application efficiencies due to its ability to apply small volumes of water directly to the plant root at

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[1] Field level application efficiency (e_a) as defined by ASCE 1978, Bos and Nugteren 1974, Hansen et al. 1980 is:

$$e_a = V_s / V_f$$

V_s = volume of irrigation water needed for evapotranspiration by the crop to avoid undesirable water stress

V_f = volume of water delivered to the field application rates less than soil infiltration rates. This minimizes surface runoff and deep percolation losses common in surface irrigation schemes. Drip irrigation also often has higher application efficiencies than sprinkler systems, as soil moisture losses due to evaporation and weed evapotranspiration are less, as water is not broadcast over the entire field. Thus, drip irrigation results in water savings permitting more crops per unit of irrigation water to be grown or to allow crop cultivation in areas where insufficient water exists for surface irrigation. This last situation has enormous implications for the expansion of irrigation onto rainfed lands.

Besides water savings, drip irrigation offers other potential advantages. Increased crop yield is often reported to be associated with switching from surface methods to drip irrigation due to an ability to schedule irrigation to deliver the optimal plant water requirement and the ability to avoid water stress at critical growth stages. Tiwari *et al.* (1998), Yohannes and Tadesse (1998), Xie *et al.* (1999), Sharmasarkar *et al.* (2001), Srinivas *et al.* (1999), among others, all found improved yield with concomitant decreases in water use in drip plots compared to surface irrigated plots.

However, crop yields do not always increase with drip irrigation. Hanson *et al.* (1997) found a statistically significant reduction in yield for drip-irrigated lettuce versus furrow irrigated lettuce, while various authors (e.g. Bucks *et al.* 1974, Sammis 1980, Hodgson *et al.* 1990) observed similar yields for both drip and surface irrigated crops. Ultimately crop yield, although influenced by irrigation methods, is a result of a combination of environmental factors.

Drip irrigation also offers the potential to reduce fertilizer consumption and waste by the application of fertilizers through fertigation rather than basal and top dressing methods. The combination of increased efficiency of inputs and reduced surface and sub-surface water losses in drip irrigation reduces agricultural pollution of groundwater and surface waters. In addition, saline or brackish water may be used in drip irrigation since frequent water applications can keep salt stress at a minimum (Sivannapan 1994). Drip irrigation has also been shown to reduce the incidence of diseases, particularly root rots, (see Xie *et al.* 1999) in comparison to surface irrigation, which may allow reductions in fungicide and pesticide applications.

From a social perspective, drip irrigation decreases the cost of cultivation particularly in labour intensive operations like weeding, irrigation, ploughing, and making furrows. Drip irrigation can also be used in hilly terrain and texturally non-uniform fields (Yohannes and Tadesse 1998).

In sum, drip irrigation offers numerous advantages and the rate of expansion of microirrigation systems has been high, 329% between 1981-1991, yet despite this large gain, microirrigation represents only ~1% of the worlds' total irrigated area and is still predominantly used only for tree crops (followed by vines and vegetables) (Bucks 1995).

10.2.1. Development of Drip Irrigation

In comparison to surface irrigation methods, which date back to 6000 BC, drip irrigation is relatively new. In 1860, the first experiments involving a combination irrigation-drainage system composed of clay pipes with open joints occurred and by the early 1960's drip irrigation was being extensively used in greenhouse research. By 1972, the Israeli's developed the first commercially automated drip irrigation systems, a precursor for modern drip irrigation systems in which field-level sensors, computers, modeling software, facilitate automated, real-time, irrigation scheduling (Phene 1995).

Drip irrigation systems were designed for fields $\geq$ 4 ha to minimize management and labour requirements. Drip irrigation, in the conventional western sense, has evolved to become a knowledge-intensive, technology-orientated, capital-intensive operation (capital costs range between US $1500-$2500 per hectare (Postel *et al.* 2001)). These "Western" drip irrigation systems are thus, unavailable, economically and technically, to approximately 95% of the world's farmers who live in developing countries characterized by landholdings of less than two hectares in size and with annual incomes that are insufficient to pay for conventional western drip irrigation (Postel *et al.* 2001).

10.2.2. Low-cost drip irrigation (LCDI)

Low-cost drip irrigation (LCDI) offers an irrigation method that is affordable, suited for small fields, and maintains the water saving advantages of Western drip irrigation systems. Globally, several different companies are developing LCDI systems including International Development Enterprises (IDE), Chapin, Netafin, and Microtal. These firms differ in system design, cost and distribution philosophy.

The LCDI systems used within Nepal are overwhelmingly those developed by IDE, a non-profit organization operating in Asia, Africa, and Central America. IDE has reduced the cost of drip irrigation systems to US $ 250 per hectare by:

1) replacing emitters (costing ~ $0.25) with a simple hole punched into the drip line. A plastic baffle placed around the hole deflects the water, creating a drip pattern. The size of the hole is the same as a safety pin, allowing clogs to be easily and inexpensively cleaned. (In contrast, emitters clogging in Western drip irrigation system are often treated through chemical means and utilize expensive filtration processes to minimize clogging).
2) replacing complex and expensive filters with a simple and inexpensive 2-step filter process. A plastic screen sieve blocks coarse material from entering the water tank, while a mesh filter at the outlet blocks fine material from exiting the water tank.
3) shiftable drip lateral lines, allowing one lateral line to irrigate multiple crop rows.
4) utilizing a low-pressure (gravity) system. This eliminates the need for expensive pumps, however drip lines are not as long as drip lines in Western systems. This ensures that large pressure differences do not occur between emitters at the upstream and downstream end of the line.

In addition, common to other LCDI systems, IDE systems are designed to be expandable, such that farmers can start with a small system (125 m^2) and expand to larger systems (500 m^2) as a farmer's individual economic situation improves. In addition, systems are designed to be easily adaptable to a variety of field sizes.

IDE uses a variety of activities, such as farm demonstrations, street theatre, training programs, and meetings to promote and expose farmers to drip irrigation. This is an essential component as few farmers are aware of the potential of LCDI or even of its existence. IDE provides technical and marketing training to local manufacturers and distributors, and agricultural assistance to farmers, many of whom have no experience in off-season vegetable production. The goal is to create a sustainable network that is demand driven and that functions independent of subsidies. (Deepak Adhikari, pers. comm., 2000). This has resulted in more than 2250 farmers using LCDI within Nepal in 2000, a dramatic increase from the initial trial 10 farmers in 1996.

It is obvious from the growth in the numbers of users and from the personal accounts by farmers that LCDI has been successful in terms of improving household food and economic security and land productivity.

10.3. Deficit irrigation

Deficit irrigation, the deliberate and systematic under-irrigation of crops is a practice employed in many areas of the world, particularly those with water shortages. Deficit irrigation can prove to be beneficial in either land-limited or water-limited scenarios by increasing irrigation efficiency, reducing the cost of irrigation, and reducing the opportunity costs of water. Deficit irrigation may enable a farmer to irrigate more land or alternatively to reduce capital/fixed costs associated with irrigation. Deficit irrigation, however, does impose a greater degree of risk on a farmer as the margin of error in determining optimum water use is often wide and the relationship between water use and crop yield is intrinsically uncertain (English and Raja 1996).

The effect of deficit irrigation will vary according to crop type, the amount of soil moisture depletion, soil type, and the phenological stage(s) at which water deficits are experienced by plants. The effect on crop yields will depend on how water stress influences the growth rate, the growth duration, and the manner in which material is partitioned to the economically important portion of the crop. For some crops deficit irrigation may detrimentally affect quality (e.g. potato), whereas in other crops it may enhance quality (e.g. increased sugar percentage in sugar beets). A simplified response to water deficits is a reduction in the duration of growth potentially leading to a smaller final biomass and yield. The effect of soil type on the available water holding capacity of the crop root zone will also affect the relationship between yield and soil moisture deficits (Jamieson 1999).

10.4. Research goal

The research goal of this study is to provide a quantitative measure of how well LCDI performs to conventional Western drip irrigation under controlled circumstances under full and deficit irrigation regimes. Both drip irrigation systems are compared to hand watering, as this may also be a potentially appropriate alternative for a Nepali farmer. Although comparisons between LCDI and the more expensive Western drip irrigation system are likely irrelevant to the average Nepali farmer (who is unable to afford the latter irrigation method) the Western drip system was included to provide a reference drip system against which LCDI could be compared.

The specific objectives of this research are:

1) to quantify and compare the operational parameters of each irrigation system. Operational parameters assessed are the mean emission uniformity, mean flow rate and its variance, and the wetted area.

2) to quantify and compare the performance of each irrigation system and the effects of deficit irrigation and different irrigation scheduling. Performance will be evaluated using soil volumetric water content and its variability and crop biomass as indicators.

Deficit irrigation, at 50 % of the recommended daily water amount, was incorporated as a treatment within this study to examine the effects of deficit irrigation on cauliflower yield and whether the effects of deficit irrigation vary among irrigation methods. This provides a general indication of how viable deficit irrigation is and also provides a rough idea of the minimum amounts of water required to cultivate an additional crop. This provides a basis to determine the minimum size of water harvesting tanks, something that is increasingly gaining popularity in water scarce areas.

For each indicator assessed two comparisons will be made:

a) a comparison between different irrigation systems operating under the same irrigation regime e.g. within deficit irrigation a comparison between LCDI, Western drip, and hand-watered.
b) a comparison between different irrigation regimes operating under the same irrigation system e.g. within LCDI a comparison between the deficit regime, morning-evening regime, and the evening-only regime.

3) to develop a soil-water retention curve to relate measured soil volumetric water content to matric potential and thus plant stress.

4) to assess the economic benefits of each irrigation method for a representative field size.

5) to determine the water use efficiency of each irrigation method.

11. STUDY SITE AND METHODOLOGY

11.1. Tamaghat: Khet Drip Experimental plot

11.1.1. Setting

A drip irrigation experimental plot was set-up on HMG Panchkhal Horticulture farm, situated at 865 meters above sea level, in the Jhikhu Khola Watershed valley bottom in the town of Tamaghat. The farm has a reliable and constant water source from an up valley spring. The land upon which the drip experimental plot lies is khet land, and thus is unlikely to require water conservation technologies to the same degree as bari land. As many farmers visit the horticultural farm to obtain seeds, seedlings, or to attend workshops this location provides a high degree of exposure for the low-cost drip irrigation system as well as a controlled research setting.

11.1.2. Rainfall and Temperature

The climate is sub-tropical. Rainfall and temperature patterns at Tamaghat mimic the overall trends for the Jhikhu Khola watershed. Average monthly rainfall for the period 1990-1996 is at a maximum in July (295 mm) and is at a minimum in December (5 mm) (Figure 11.1). The mean annual temperature is 21.2 °C , with a mean daily max of 28.1 °C and a mean daily min of 14.2 °C. Temperatures are greatest during the late pre-monsoon and the monsoon season, with average temperatures typically greater than 30 °C. With winter, average temperatures decline reaching their lowest levels in December/January, although minimum temperatures rarely go below freezing (Figure 11.2). Temperature inversions occur in the valley area during the winter due to morning fog (Carver 1997). The experiment was run from October 17, 2000 to January 16, 2001. During this time period, only two light rainfall incidents occurred, the first on Oct. 24th and the second on December 31st, 2000. The weather was otherwise sunny, although morning fog was typically present during November, December, and January.

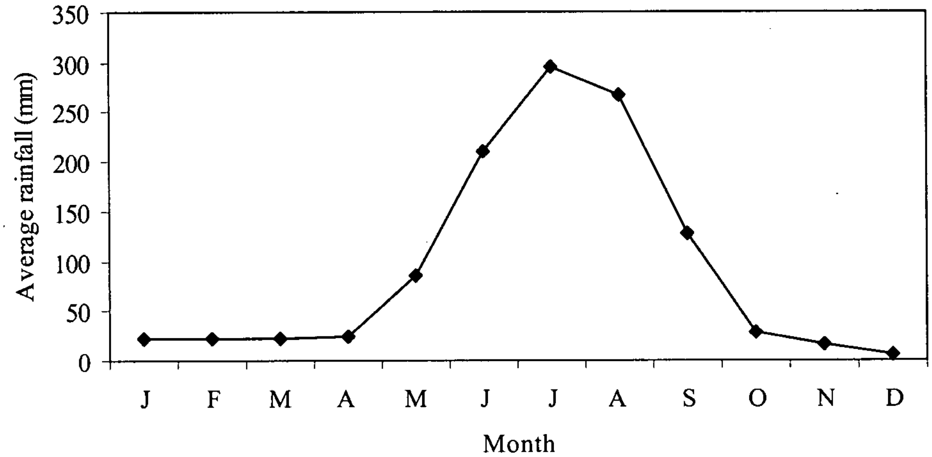

Figure 11.1 Average monthly rainfall (mm) at Tamaghat (1990-1996) (Carver 1997).

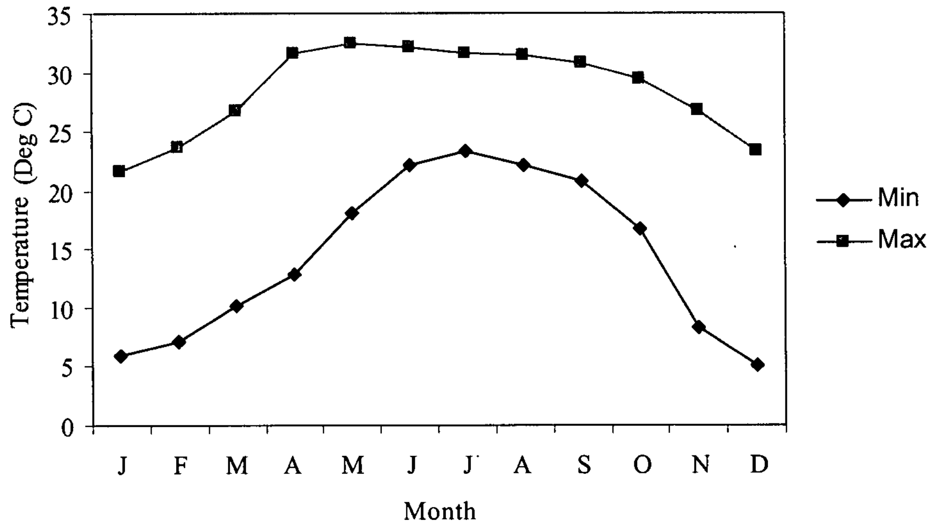

Figure 11.2 Mean monthly min/max air temperature at Panchkhal (1978-1994) (Carver 1997).

11.1.3. Soil type

The soil is a non-red sandy-clay loam soil with 42 % sand, 27 % silt, and 31 % clay. Soil chemical properties are presented in Table 11.1. The surface bulk density is 1180 kg/m^3.

Table 11.1 Soil chemical properties of irrigation plot (0-15 cm depth)

Soil variable	Mean value (n=10)		Soil variable	Mean value (n=10)
PH ($CaCl_2$)	5.6		Base saturation (%)	65.6
CEC	9.6		Carbon (%)	1.29
ex-Ca (cmol/kg)	4.57		Nitrogen (%)	0.11
ex-K (cmol/kg)	0.41		Available P (mg/kg)	148.3
Ex-Mg (cmol/kg)	1.28			

11.2. Drip Irrigation: Field Methodology

11.2.1. Irrigation equipment

Three irrigation methods were used in the experiment: low-cost drip irrigation, Western drip irrigation, and hand-watered (HW). A medium size LCDI unit capable of irrigating 250 m^2 was utilized. Each lateral line of the LCDI was used to irrigate only one row, although lateral lines are designed to allow shifting for the irrigation of multiple rows. The LCDI systems used was developed by International Development Enterprises (IDE) and produced in Nepal. The Western drip system used was a conventional North American drip irrigation system purchased in Canada. This system will be called "Western" in the remainder of the text. The specifications for the drip systems are provided in Table 11.2. Watering by hand was conducted with a pail of water and a plastic container, cut to the appropriate volume, so that water could be scooped from the pail easily and accurately.

Table 11.2 Specifications of main line, lateral line, filter type, and emitter type and spacing of drip irrigation systems utilized.

System	Main line	Lateral line	Filter type	Emitter type	Emitter spacing
LCDI	13 mm PVC (soft)	8 mm PVC (soft)	Jerry can and net + top screen	Baffle (flow rate = 2.2 lph*)	60 cm
Western	13 mm PVC (semi-rigid)	13 mm PVC (semi-rigid)	19 mm inline Wye filter + IDE filter type	Rainbird™ Xeri-Bug (flow rate =1.89 lph pressure compensated)	60 cm (spacing is determined by user)

*lph = litres per hour, flow rate according to manufacturer's specifications.

Water was stored in a 100 L drum that was elevated 1 meter above the ground on a bamboo tripod. A clear plastic pipe attached to the "Multi" (drum outlet on-off valve) showed the water level within the drum. One litre aliquots of water were added to the drum until it was full, with each addition marked with an indelible marker on the clear pipe, thereby calibrating the drum into 1L units.

11.2.2. Flow rates

Flow rate was assessed via a series of field trials at the beginning of the experiment. The amount of water released from each emitter within a specified unit of time was collected in a cylinder and subsequently measured. Throughout the remainder of the experiment flow rate was monitored by determining the amount of time required to deliver a specified volume of water. The initial volume of water within the tank was noted to determine if a correlation between flow rate and pressure existed.

11.2.3. Site Preparation and Field Set-up

A 156 m^2 plot at the Panchkhal Horticulture Farm was rotor-tilled 2 weeks prior to planting. Holes of ~ 30 cm depth were dug in the location where cauliflower seedlings were to be planted. A generous handful of compost was placed into the holes after which they were re-filled with soil. The digging of holes and compost addition occurred two weeks prior to the planting of cauliflower for the drip irrigation rows, however only 2 days prior to the planting of hand watered (HW) rows. The difference in timing was due to a shortage of farm labour with the commencement of the major Dasain holiday.

The plot was divided into ten lines: 3 lines under LCDI (Lines D1, D3, and D5), 3 lines under Western drip irrigation (Lines D2, D4, and D6) and 4 lines that were hand watered (Lines HW1-HW4) (Figure 11.3). Each line had 2 replicate lines. Each replicate line was 12 m long, 90 cm wide, and consisted of 20 plants. Spacing between plants within a line was 60 cm, as this is the spacing of the LCDI emitters, while spacing between plants of replicate lines was 45 cm. Inter-row spacing was 60 cm except for a 1 m space between the drip and HW treatments.

11.2.4. Irrigation treatments

The three different irrigation treatments applied to each irrigation methods are outlined in Table 11.3 and Figure 11.3.

Table 11.3 Irrigation treatments of the experimental plot at Tamaghat.

Name	Month 1 watering regime				Month 2 and 3 watering regime			
	Application				Application			
	Volume (mL/ plant)	Time	Frequency	Daily total (mL/plant)	Volume (mL/ plant)	Time	Frequency	Daily total ML/plant
Morning-Evening (ME)	113	Morning and evening	Daily	226	350	Evening	Daily	350
Evenings only (EO)	226	Evening	Daily	226	750	Evening	Alternate days	350
Deficit (D)	226	Evening	Alternate days	113*	350	Evening	Alternate days	175*

This value represents the average daily total over two days. In fact, deficit (D) irrigated plants received water only every alternate day.

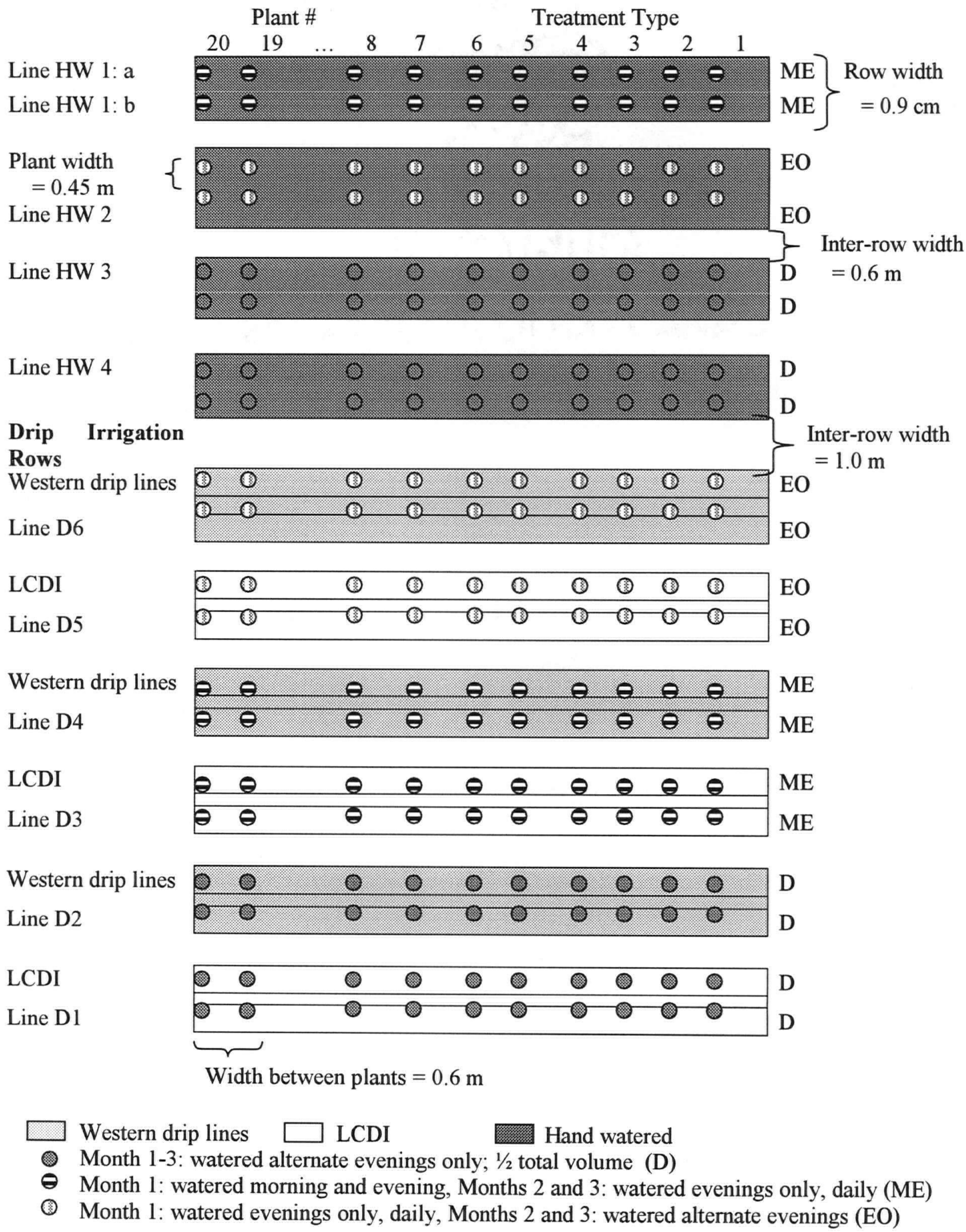

Figure 11.3 Set-up of irrigation experimental plot.

As illustrated in Figure 11.3, the Morning-Evening watering regime applies to lines D3, D4 and HW 1, the Evening-only watering regime applies to lines D5, D6, and HW 2, and the Deficit watering regime applies to line D1, D2, and HW 3 and HW 4. The deficit irrigated plants received 50% of the full water volume required. The amount of water required by each plant was determined by Equation 1 (Raindrip Inc. 1983). The formula was developed in imperial units and was thus used with parameters measured in imperial units, however the final volume determined was converted to mL/plant/day.

$$W = (0.4983 \times D \times D \times PF \times ET_0) / EF$$

Equation 1 Per plant daily water requirement

where,

W = Daily water requirement per plant (gallons/day/plant) (see Table 11.4)

D = Diameter of the plant's canopy (feet)

PF = Plant factor (PF = 1.0 for vegetables, flower beds, container plants, fruit bearing trees, shrubs under 4 feet high) (unitless)

ET_0 = potential evapotranspiration ("/day)

EF = irrigation efficiency. Irrigation efficiency depends on climatic conditions, as climate is considered "moderate" an EF value of 0.90 is given by International Development Enterprises (IDE)

The coefficients used in the calculation of the daily plant water requirements are presented in Table 11.4.

Table 11.4 Parameters for calculating the daily water requirement per plant at Tamaghat.

Parameters for the calculation of daily per plant water requirement					
Growth Period	D	Plant factor	ET_0 (" /day)	EF	Water vol/day (US gallons)
Month 1	1.0	1.0	0.108	0.9	0.059
Month 2 & 3	1.5	1.0	0.081	0.9	0.099

Based on Table 11.4 the daily plant water requirements in metric units are 226 mL/plant/day for Month 1, and 375 mL/plant/day for Month 2.

Values for potential evapotranspiration were calculated and provided by PARDYP (People and Resource Dynamics Project) (Madhav Dhakal, pers. comm. 2000). Data for ET calculations were gathered from nearby hydrometerological stations. Pan evaporation data was unavailable and access to an evaporation pan during the study was not possible.

Equation 1 was used to determine water volumes within the experiment for several reasons. First it is the formula IDE recommends to its farmers and is thus the parameter under which LCDI operates in Nepal. The use of soil matric potential, which would have allowed irrigation volumes to be based on plant need, was not possible as the use of tensiometers and gypsum blocks was rejected for this study due to the potential for soil cracking resulting in poor contact and erroneous readings. In addition it was not possible to adjust water volumes based on volumetric water content measurements and a soil water retention curve, as the only pressure plates within Nepal were under repair for the duration of the trial. Equation 1 is thus the most realistic choice given the field conditions within Nepal.

11.2.5. Soil water measurements

Measurements of volumetric soil water content were made with a Hydrosense™ probe for an average depth of 12 cm or 20 cm. The probe consists of two parallel stainless steel probes that are sensitive to dielectric permittivity and consequently water content. The reading is an average of the total length of the probe (either 12 cm or 20 cm). Measurement accuracy and range for the unit and the probe may be found in Appendix 2.

Spatially, measurements were taken at 5 locations for each plant measured: at the zero point (ZP), and at 6 cm and 12 cm away from the ZP on either side of the plant in the direction of the crop row (Figure 11.4). The zero point was considered to be at the drip emitter for drip-irrigated plants and at the stem of the plant for hand-watered plants.

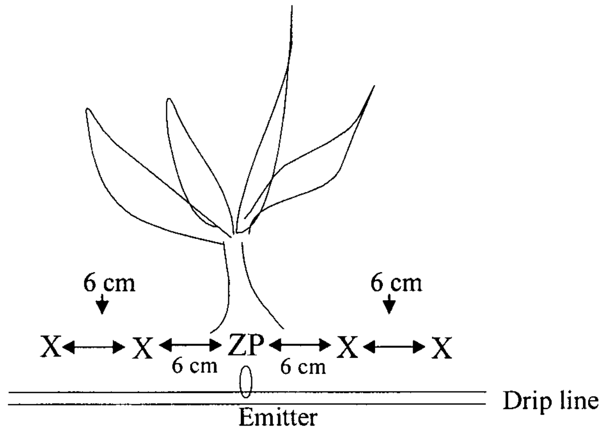

Figure 11.4 Spatial location of volumetric water content measurements.

Temporally, measurements for lines being irrigated were taken before and after irrigation. Measurements that were taken after the morning irrigation are labelled as "post AM irrigation", and those after the evening irrigation as "post PM irrigation". Lines that were not irrigated on a measurement day were measured once in the morning and once in the evening. Measurements taken in the morning and in the evening are labelled as AM and PM respectively, and were taken prior to irrigation, regardless of whether or not irrigation occurred. Measurements were not taken after December 22nd when the harvesting of cauliflower began.

11.2.6. Fertilizer application

Prior to planting, fertilizer was applied to the soil where the cauliflower would be planted. Fertilizer doses throughout the experiment were based upon the recommendations of the Horticulture Farm's technical advisor Mr. Gopi. The initial dose per plant was: 4.34 g of diammonium phosphate (DAP) (18:46:0, N:P:K), 2.71 g urea (46:0:0, N:P:K), and 2.08 g potash (0:0:60, N:P:K). A top dressing of 2.16 g of urea was applied to the drip irrigated plants by fertigation and to the soil for HW plants on November 14th, 2000. Foliar sprays of Agromin™ and Multiplex™ were applied to the plants to treat emerging micronutrient deficiencies.

Table 11.5 Date and amount of micronutrient spray applied

Date	Type	Total Amount Applied to 400 plants
Nov. 2	Agromin	10 L
Nov. 16	Agromin	30 L
Dec. 15	Multiplex	20 L

11.2.7. Pesticide Use

Pests that affected cauliflower in this plot were limited. The presence of cut worm (*Agrotis ipsilon*), a green caterpillar likely *Plutella xylostella*, and a flea beetle (*Ophrana lhobote*) were noted. *A. ipsilon* was the cause of mortality for several cauliflowers, particularly at the seedling stage. More persistent were aphids feeding on the young succulent leaves. Aphid infestation initially developed in the greenhouse. In an attempt to control aphid populations 10 L of *Titepate*, a local Artemisia-based organic pesticide was sprayed followed by 10 L of Nuvan™ on Nov. 1st, 10 L of Roger™ on Nov. 6th, and 30 L of Roger and 20 L of Malathin™ on Nov. 15th. Malathin, Roger, and Nuvan are all broad based insecticides available locally. Despite these efforts a limited effect was observed on the aphid population, and thus over the course of several days the aphid population was culled by hand.

11.2.8. Cauliflower planting

A hybrid variety of cauliflower, Snowcrown, from the Karki Seed Company was used. Snowcrown requires 90 days from the transplantation date to reach maturity, while the local cauliflower variety requires 180 days. All seedlings planted in Tamaghat were procured from the on-farm greenhouse. Seedlings were 36 days old at transplantation. Drip irrigated seedlings were planted on the evening of October 16, 2000 into unirrigated soil and subsequently irrigated. Likewise, HW plot seedlings were planted on the evening of October 17, 2000.

Over the course of the study 13 cauliflower plants were replaced in the drip irrigated rows and 14 in the hand-watered lines of a total 400 plants. Replacements were made as a result of to insect damage, growth deformity, or mortality in the establishment phase. Eleven seedlings replanted late in the experiment were unintentionally replanted with the cauliflower variety Snowball-16, a 4-month hybrid variety. Yield data from these plants were not considered.

11.2.9. Cauliflower harvest

Cauliflower were considered mature when the inner leaves began to pull away from the fruit and the florets began to loosen when lightly pressed. At this point, the height of the tallest leaf and plant width at the widest point was taken with a tape measure, after which the stem was cut with a hacksaw at the soil-air interface. Total aboveground biomass was weighed, after which all leaves were removed and counted. Cauliflower heads were cut from the stem, weighed and measured. Roots were dug out and root depth was measured. The maximum lateral and vertical depth of the root system was determined for eleven plants. Soil was removed from the plant root systems of these plants by careful excavation and washing of the root system in a 0.75m radius area from the plant stem.

11.3. Laboratory methods

11.3.1. Drip irrigation samples

Soil samples at the drip irrigation site were collected prior to the commencement of the experiment. Ten samples were randomly collected within the irrigation plot. In addition to testing the same chemical parameters as the soil fertility samples, selected soil physical properties were determined. Particle size was determined via the hydrometer method and soil moisture retention curves were obtained from soil surface cores (height = 3 cm). Cores were saturated and placed under pressures of 2.5 kPa, 5.0 kPa, 10 kPa, 20 kPa, 40 kPa, 80 kPa using a 100 kPa high flux pressure plates. Measurements were taken at each pressure after equilibration.

12. OPERATIONAL PARAMETERS

Testing operational parameters was not the focus of this research, however, to run and manage the system, field-testing of operational parameters was necessary. An assessment of operational parameters provides information on whether the irrigation systems are operating according to their expected (manufacturer stated) performance as well as providing insights into potential variation in crop yields. The results are presented here with the caveat that in depth operational testing was not conducted.

12.1. Emission Uniformity

The emission uniformity (EU) of a drip system is a measure of the degree to which individual emitters uniformly emit water throughout the entire drip system. A low EU will result in over and/or under irrigating plants, which may negatively impact crop yield and will decrease the overall irrigation efficiency of the system and increase the variability of yields within a line. The overall EU of a system is influenced by changes in water pressure, temperature, operational factors, such as emitter clogging and leaks, and the manufacturer's coefficient of variation (v_m).

The manufacturer's coefficient of variation represents the anticipated variations in discharge in new emitters due to differences in the manufacturing process (Keller and Bliesner 1990). A manufacturer's coefficient of variation of 0.05 indicates that 68% of the emitter flow rates are within $\pm$ 5% of the mean, and 95% of the flow rates are within $\pm$ 10% of the mean. Thus emitters with low v_m values are expected to result in less overall flow variation.

Currently, no industry standards exist as to how v_m values are obtained. Thus, cited v_m values often provide little or no information on the number of emitters tested, the water pressure and temperature at which tests were conducted, when tests were last conducted, or the duration for which tests were conducted. Due to the lack of standardized procedures in measuring v_m values, Rainbird does not publish a value for the Xeri-bug™ emitter used in this experiment (although flow tests are conducted during the production process). It is expected that the v_m will fall within average performance values for emitters of its type ($0.3 < v_m < 0.7$) (Dean Dal Ponte, Rainbird representative, pers. comm. 2002). The manufacturers coefficient of variation for IDE baffle emitters at a head of 2 m is 0.16 (Polak *et al.* 1997).

To test the emission uniformity within the field the following formula, developed by Keller and Bliesner (1990), was used:

$$EU' = 100\, q'_n/q_a$$

Equation 2 Field-tested emission uniformity

where

EU' = field test emission uniformity

q'_n = average rate of discharge of the lowest one-fourth of the field data emitter discharge readings (L/hr)

q_a= average discharge rate of all the emitters checked in the field (L/hr).

Table 12.1 Mean field-tested emission uniformity of individual drip lines.

Manufacturer: Line #	Mean field-tested emission uniformity (%)	Number of trials
LCDI: Line 1	65	3
LCDI: Line 3	79	5
LCDI: Line 5	75	6
Western: Line 2	63	4
Western: Line 4	64	5
Western: Line 6	66	6

Overall, the uniformity of LCDI emitters was typically greater than those of Western drip lines (Table 12.1). The emission uniformity of Rainbird emitters was less than expected and likely indicates that the water pressure was insufficient to seat the diaphragm correctly within the pressure compensating emitters. The use of a non-pressure compensating emitter would likely have resulted in a more uniform distribution (Dean Del Ponte, Rainbird representative, personal communications, 2002). The emission uniformity of IDE emitters ranged between 65-79%. Systems with a field-tested emission uniformity between 70-80% are considered as “fair”. Although the LCDI generally had better emission uniformity than Western lines this finding should not be generalized to conditions in which water flow is pressurized. It would be expected that Western emitters with adequate head would have had comparable emission uniformity to those of LCDI emitters.

12.2. Flow rate

Flow rates were assessed for individual emitters for each replicate line pair. No significant difference in mean flow rate was observed for any replicate lines pairs except Line 4 (Western drip) in which the flow rate of one of the replicate lines was significantly higher than the other (Mann-Whitney U, $\alpha < 0.05$, 5 trials). The reason for the discrepancy in flow rate between line 4a and 4b is not know. Median flow rates for each of the lines is presented in Table 12.2.

Table 12.2 Median flow rate of drip irrigation lines.

Line # (Irrigation method)	1 (LCDI)	2 (Western)	3 (LCDI)	4 (Western)	5 (LCDI)	6 (Western)
Median flow rate (L/hr)	2.8	2.0	3.9	2.4	3.3	0.9

Differences in flow rates were tested within groups and between groups. Within LCDI lines flow rates between drip lines 1, 3 and 5 were not statistically different, although median flow rates appeared to decrease with increasing distance from the water source (Line 3 flow rate > Line 5 flow rate > Line 1 flow rate). Western drip line 6 had a significantly lower flow rate than either line 2 or line 4.

Between groups, the flow rates of LCDI lines 3 and 5 were significantly greater than all western drip lines, while the flow rate of LCDI line 1 was significantly greater than Western drip lines 2 and 6.

12.2.1. Flow rate and pressure

Flow rate was not significantly correlated to pressure (determined as the height of the water head) for western drip lines, however it was positively correlated to LCDI lines 3 ($r^2 = 0.41$) and 5 ($r^2 = 0.58$). This was expected as water travels through a tortuous pathway within Rain Bird emitters before being released thus minimizing pressure effects. In LCDI, only the size of the opening within the line and any deflection effects of the baffle surrounding it will limit water flow rate. The lack of a significant correlation to LCDI line 1 was surprising, and likely indicates that Line 1 is sufficiently far away from the water source that the effects of water pressure are dampened.

12.2.2. Wetted area

The wetted area around each plant was measured at the soil surface only in four directions (Figure 12.1) from either the emitter (in the case of drip lines) or the plant stem (in the case of bucket lines) to obtain an approximate size of surface wetted area.

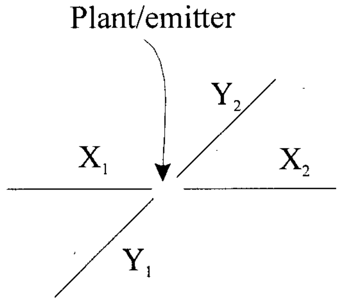

Figure 12.1 Schematic representation of the measurement method of the wetted area.

No significant difference was observed in either the lateral ($x_1 + x_2$) or vertical dimension (y_1+y_2) between replicate pairs for all drip and hand watered lines (Mann-Whitney U, α <0.05). For all individual replicate lines measured, the wetted area significantly increased in both lateral and vertical dimensions after November 20th, the date at which an increase in applied water occurred to accommodate the latter growth stage of the plants (Mann-Whitney U, α <0.05).

Within the three different irrigation regimes (deficit irrigation (D), morning-evening (ME), and evening-only (EO) the wetted area for hand watered plants was significantly greater than drip lines. This indicates that the degree of lateral and vertical spread is greater in the hand-watered plots. This is expected, as water when applied by hand is not applied at a point source as in drip irrigation, thus potential splash may cause a greater spread of the wetted area. No significant difference between LCDI and Western lines was determined.

12.3. Summary: Operational parameters

The LCDI lines had higher emission uniformity than Western drip lines, but also higher flow rates. The flow rate between replicate lines were not significantly different for all lines except line 4, in which flow rates between replicate lines differed significantly. LCDI lines appear to be more sensitive to the water head than Western drip irrigation, resulting in positive correlation between flow rate and water head for LCDI lines 3 and 5. This effect appears to be relevant only to those lines close (~ within 3 m) to the water source; at greater distances the influence of pressure appears to be dampened. This has implications to farmers who use a larger sized water tank (e.g. 100 L rather than 50 L), situate their water tank at a higher head, and those that base the amount of water to be released on a time interval (typically the method most farmers use). If farmers are unaware of potential variation in flow rate with water head, it may result in the over-irrigation of lines close to the water source. Additional trials are required to determine at what head pressure becomes an influencing variable of flow rate, the distance from the source at which pressure effects are sufficiently dampened, and whether increased flow rates and potential over irrigation results in significant differences in crop yield and significant water losses.

13. SOIL VOLUMETRIC WATER CONTENT

This chapter examines the performance of the irrigation systems and regimes in terms of soil volumetric water content and the associated soil-water retention curve. The soil volumetric water content (SVWC) was measured over the course of the experiment for each line in the morning (AM), in the evening prior to irrigation (PM) and in the evening immediately after irrigation (post-PM irrigation). For the ME irrigation regime, measurements were also taken after the morning irrigation that occurred within the first month (post AM irrigation). Comparisons were made either:

a) between irrigation methods within a particular irrigation regime, or
b) between irrigation regimes within a particular irrigation method.

The application of water by hand poses the potential for water to spill and not be applied directly to the plant. All efforts were made to apply water in a realistic and unbiased manner. The expectation was that any differences in SVWC between methods would indicate lower SVWC in hand-watered lines due to a greater likelihood that water is not applied directly to the plant root as in drip irrigation.

13.1. Comparison between irrigation methods within an irrigation regime

13.1.1. Deficit irrigation: SVWC of LCDI vs. Western drip vs. Hand watered.

Under deficit irrigation, there was no statistical difference in the SVWC between irrigation methods for the AM measurement. However, at the PM measurement, the SVWC in the hand-watered method was significantly greater than in both the LCDI and Western drip methods. After the PM irrigation event, Western drip lines continued to have significantly lower SVWC than both LCDI and hand-watered irrigation methods. No significant difference in SVWC was present between LCDI and hand-watered at the post-PM irrigation measurement.

It is not expected that the significant differences observed in SVWC were caused by differential drainage rates or by climactic variability across the field. The low SVWC of Western drip lines may be related to two factors: a low emission uniformity causing differential water application to plants and the effect of very small water applications. Within the Western drip lines it was observed that emitters may slowly drip after an irrigation event, thus resulting in no difference in AM measurement values despite lower levels immediately after an irrigation event. This would not be a factor in either the LCDI or the hand-watered where irrigation events are much more discrete events. The lower SVWC of LCDI at the PM measurement may be due to greater plant evapotranspiration, as overall cauliflower yield was significantly greater under LCDI (see Section 14.1.1). Of the three irrigation methods, the variability in the SVWC was greatest in Western drip (Table 13.1). This is again likely due to the low emission uniformity.

Table 13.1 Mean soil volumetric water content over 12 m depth of deficit irrigated lines for each measurement time.

	Mean soil volumetric water content (%) ± standard deviation		
	D1 (LCDI)	D2 (Western)	HW 4 (Hand)
AM	14.3 ± 4.3 n=564	14.8 ± 5.6 n=564	14.6 ± 3.9 n=564
PM	10.2 ± 2.8 n=476	11.0 ± 4.7 n=486	11.3 ± 3.5 n=486
PM: post irrigation	18.2 ± 7.7 n=258	17.1 ± 8.6 n=258	18.1 ± 5.7 n=228

Despite significant differences in the soil volumetric water content, Table 13.1 indicates that the absolute difference in the means is small, only 0.5% at the AM measurement, 1.1% in the PM measurement, and 1.0% in the post-PM irrigation measurement. Therefore, the effects of significant differences in SVWC on plant performance will likely be inconsequential.

Figure 13.1 to Figure 13.2 depict the changes in the SVWC over a 12 cm depth from October 17 to December 22 for measurements taken at AM, PM, and post-PM irrigation. The X-axis represents the number of days from the initiation of the experiment progressing from October 17th to December 22nd. The switch to greater water volumes on November 20 is represented with a dashed vertical line.

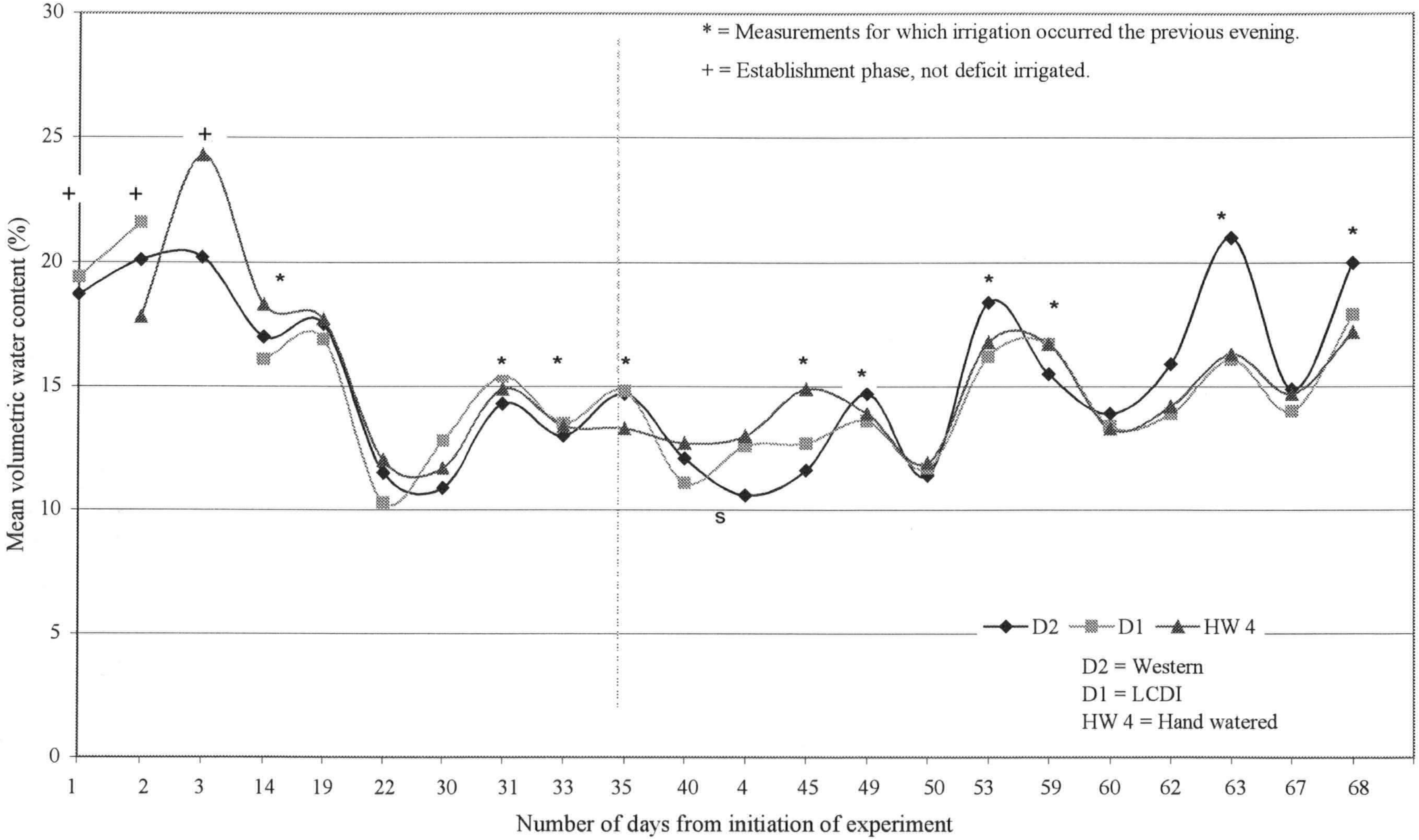

Figure 13.1 Mean volumetric water content over a 12 cm depth at the AM measurement interval of deficit irrigated lines.

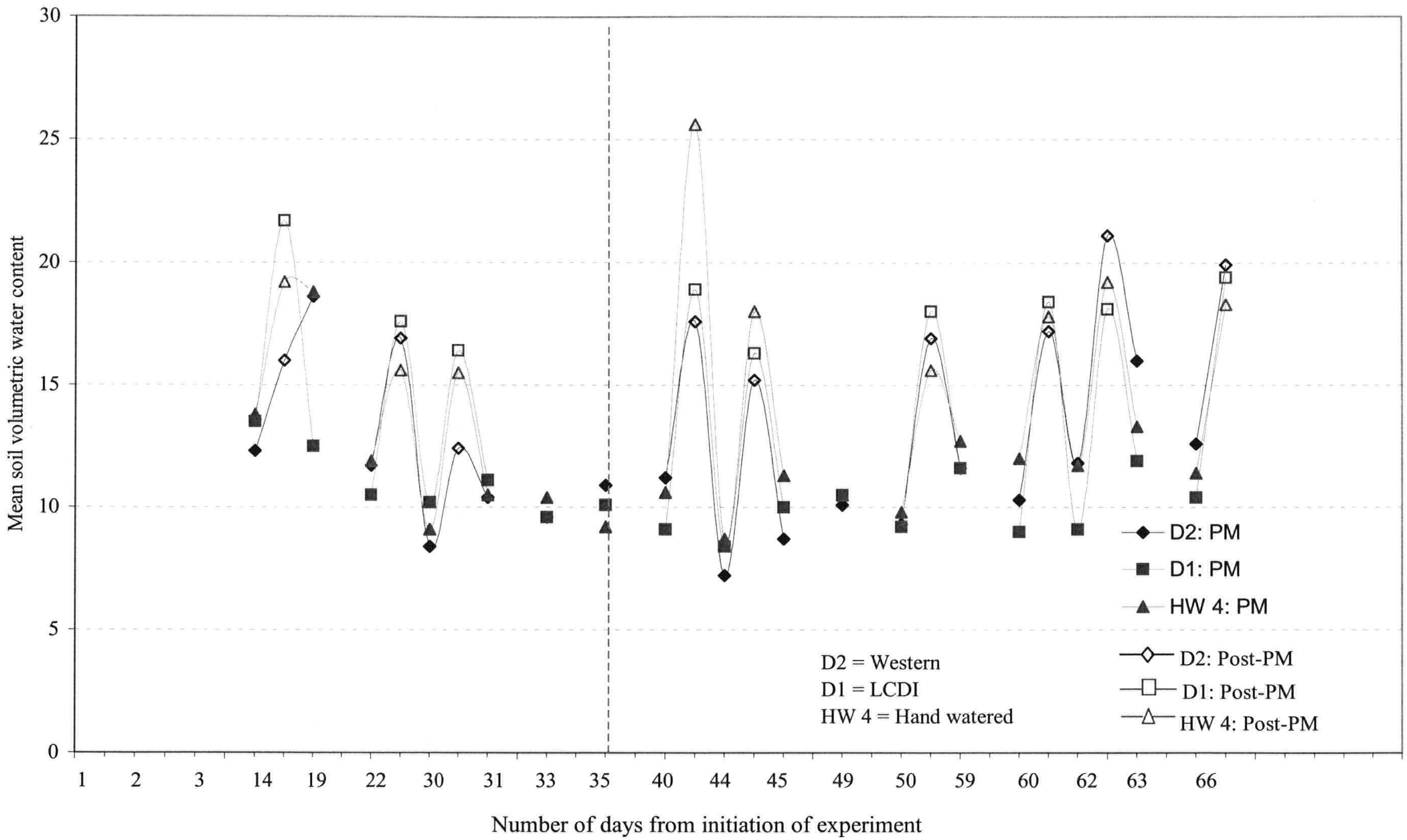

Figure 13.2 Mean volumetric water content over a 12 cm depth at the PM measurement interval of deficit irrigated lines.

Trends in the SVWC between the different irrigation methods are similar. In the AM measurement, SVWC is initially high as plants received greater amounts of water to allow establishment of transplants. Towards the end of the measurement period a gradual increase in the mean SVWC occurred in all of the lines, reflecting the increase in the irrigation volume at the later growth stages. Soil moisture levels were highest for those AM measurements taken after an irrigation event the previous evening (Figure 13.1). The SVWC was at a minimum for those PM measurements in which water had not been applied for 48 hours (which was immediately prior to irrigation) (Figure 13.2).

13.1.2. Evening-Only irrigation regime SVWC of LCDI vs. Western drip vs. Hand watered.

In the evening-only irrigation regime there was no significant difference in SVWC between the three irrigation methods for any of the measurement intervals (AM, PM, post PM irrigation). Mean SVWC values were at a maximum immediately after irrigation (~ 21%) and at a minimum (~14%) just prior to irrigation (Table 13.2). The lack of a significant difference indicates that under this regime, the irrigation method had no discernable effect on the SVWC. Similar to deficit irrigation, variability among the three irrigation methods was again greatest in the Western drip method (Table 13.2).

Table 13.2 Mean soil volumetric water content of evening-only irrigated lines for each measurement time.

	Mean soil volumetric water content (%) ± standard deviation		
	D5 (LCDI)	D6 (Western)	HW 2 (Hand)
AM	17.5 ± 5.5 n=612	17.8 ± 6.9 n=611	17.5 ± 5.1 n=618
PM	13.6 ± 4.7 n=486	14.1 ± 5.7 n=476	13.4 ± 4.5 n=492
Post PM Irrigation	21.1 ± 9.1 n=306	21.3 ± 9.9 n=296	20.6 ± 6.4 n=310

Irrigation values in the AM measurement were greatest for mornings following an irrigation event after November 20th (Figure 13.3). After Nov. 20th, the range between the low SVWC at the PM measurement and the high post PM irrigation SVWC increased as the interval between irrigation events increased from 24 hours to 48 hours (Figure 13.4). Trends in the fluctuations of the SVWC are similar for all three irrigation methods.

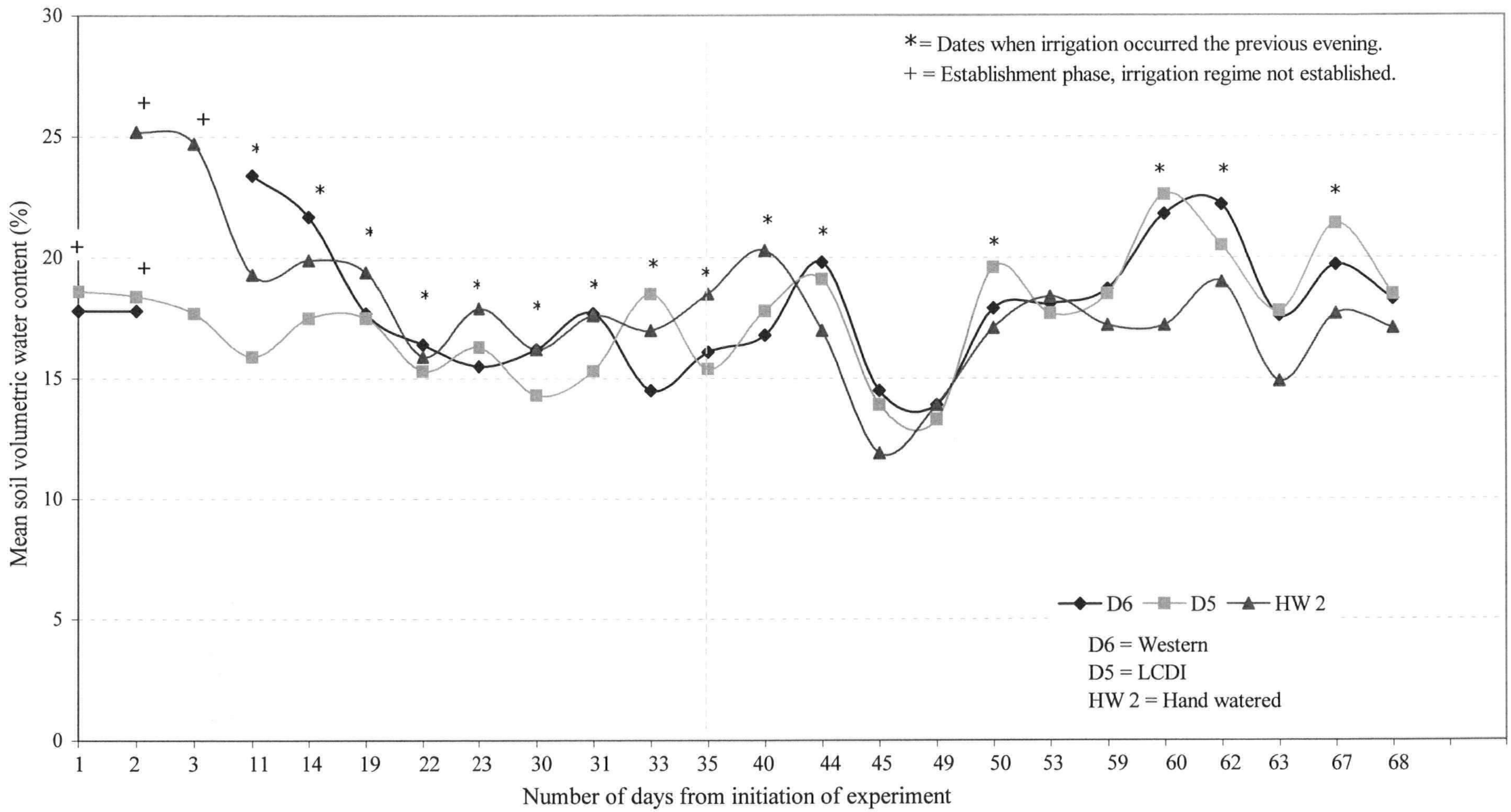

Figure 13.3 Mean volumetric water content over a 12 cm depth at the AM measurement interval of evening-only irrigated lines.

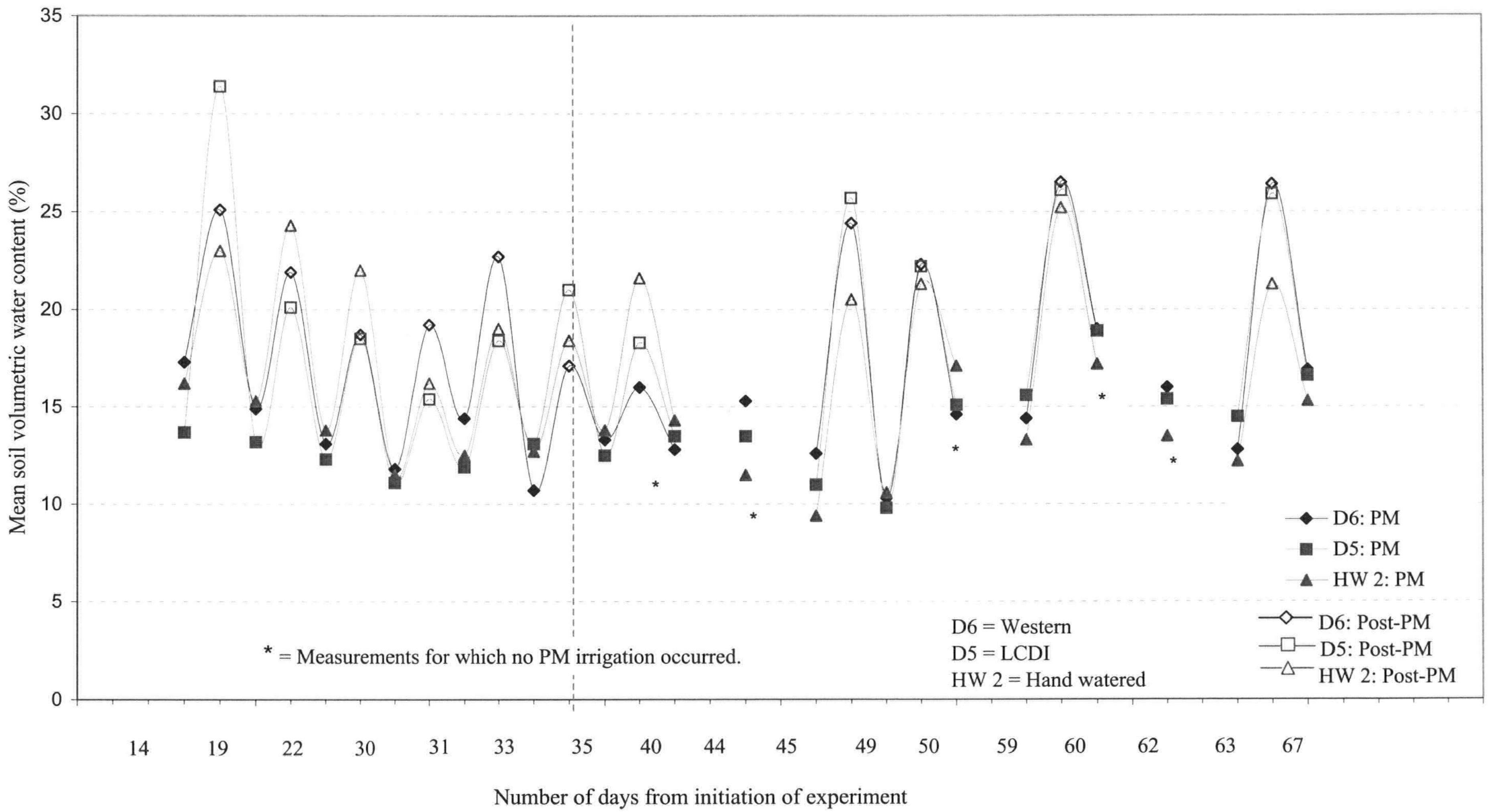

Figure 13.4 Mean volumetric water content over a 12 cm depth at the PM and post PM irrigation measurement interval of evening-only irrigated lines.

13.1.3. Morning-Evening irrigation regime SVWC of LCDI vs. Western drip vs. Hand watered.

Under the morning-evening irrigation regime statistical differences in the SVWC occurred for each of the measurement times. Lines irrigated by LCDI had significantly greater SVWC than both Western drip and hand-watered lines at all measurement intervals (AM, post AM irrigation, PM, post PM irrigation) (Figure 13.5 and Figure 13.6). In addition, Western drip irrigation had significantly greater SVWC than hand-watered lines for AM, PM, and post PM irrigation measurements. No statistical difference between Western drip lines and hand-watered was observed in the post-AM irrigation measurement.

Unlike deficit irrigation in which the maximum difference in the mean SVWC between lines was small (1.1%), the maximum difference in mean SVWC between morning-evening lines was considerable, ranging from a difference of 5.7 % in the post-AM irrigation measurement to 9.2 % in the post-PM irrigation measurement (Table 13.3). This is expected to have an influence on plant performance. Variability in the SVWC was considerably lower in the hand-watered lines than in either of the drip lines.

Table 13.3 Mean soil volumetric water content of morning-evening irrigated lines for each measurement time.

	Mean soil volumetric water content (%) ± standard deviation		
	D3 (LCDI)	D4 (Western)	HW 1 (Hand-watered)
AM	21.2 ± 7.6 n=666	18.4 ± 7.1 n=672	14.6 ± 4.6 n=656
Post AM Irrigation	22.2 ± 8.9 n=234	17.2 ± 7.6 n=231	16.5 ± 6.2 n=237
PM	18.0 ± 7.0 n=486	15.3 ± 7.2 n=486	10.8 ± 3.9 n=469
Post PM Irrigation	24.6 ± 10.0 n=486	20.0 ± 9.9 n=486	15.4 ± 5.1 n=469

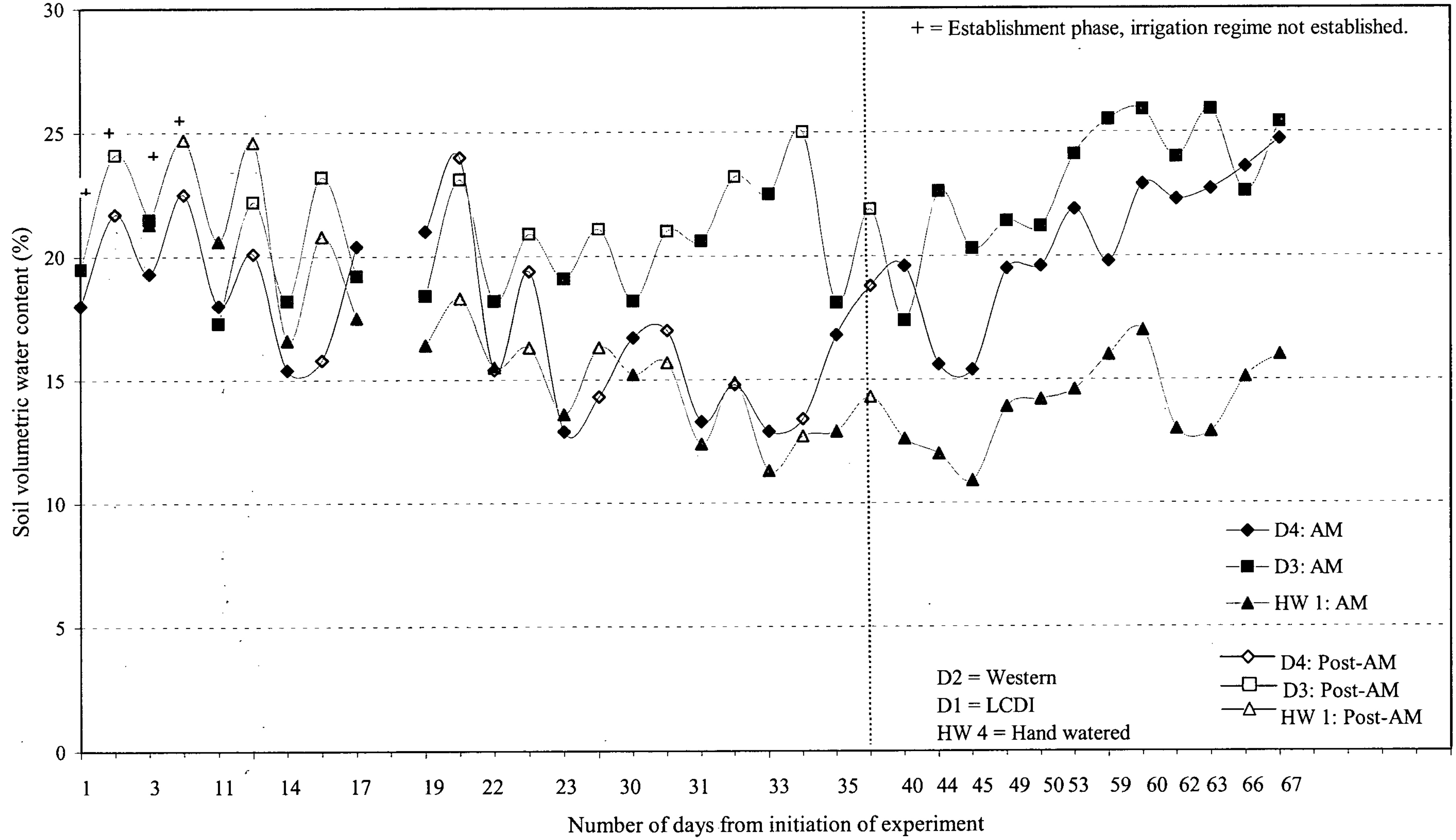

Figure 13.5 Mean volumetric water content over a 12 cm depth at the AM and post AM irrigation measurement interval of morning-evening irrigated lines.

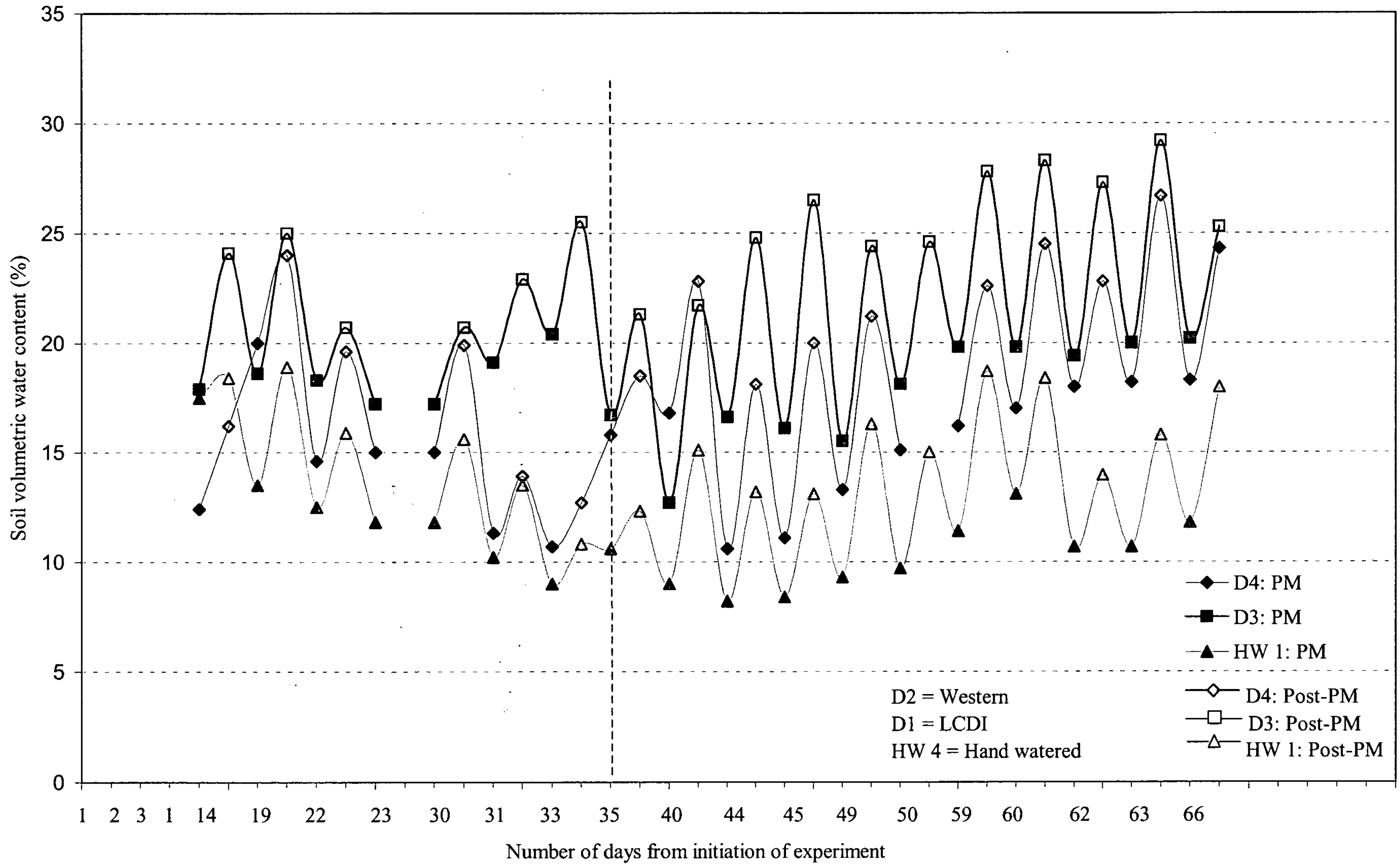

Figure 13.6 Mean volumetric water content over a 12 cm depth at the PM and post PM irrigation measurement interval of morning-evening irrigated lines.

The significant differences in the SVWC between the three irrigation methods under morning-evening was surprising as the trends within this regime are dissimilar to trends in either the deficit irrigation or the evening-only regime. In the former regime differences were significant, but small, and for the latter regime SVWC differences were not significant. Conclusive answers to why the SVWC is significantly greater in both drip methods cannot be given. It is possible that applying water by drip irrigation rather than by hand is the cause of the significant difference; water is more likely to be within a 12 cm radius of the plant root (the zone of measurement) under drip irrigation than in hand-application. However, this phenomenon should then also occur under deficit irrigation, which it did not. Alternatively, as the hand-watered irrigation line had significantly greater production of biomass, crop residue, and cauliflower mass than both of the drip methods (see Section 14.1.2) resulting in sufficiently increased transpiration within the hand-watered lines, lowering the SVWC.

13.2. Deficit vs. Morning-evening vs. Evening-only irrigation lines

As deficit irrigated lines received 50 % less water than fully irrigated lines, it was expected that the soil volumetric water content under the deficit irrigation regime would be significantly less than both the morning-evening lines and the evening-only irrigation regimes, regardless of irrigation method or measurement time. This occurred in both the LCDI and the Western drip lines. However, in hand-watered irrigation the SVWC of deficit irrigation was only significantly less than the evening-only regime but was significantly greater than the morning-evening regime at all measurement times. This demonstrates that the SVWC of the hand-watered morning-evening line was uncharacteristically low in comparison to the other lines. The production of crop residue, cauliflower mass, and biomass were not significantly different between the evening-only and morning-evening irrigation regimes, thus transpiration is likely only a contributing factor to differences in SVWC rather than a dominant factor.

13.3. Matric potential and soil volumetric water content

The soil-water retention curve was determined from 6 soil cores over a pressure range of 25 cm to 800 cm and is presented in Equation 3. The equation for the curve is:

$$\theta = 0.32\,(\psi/25)^{-0.12}$$

Equation 3 Soil-water retention curve equation

where: θ = volumetric water content

ψ = pressure applied (cm).

The r^2 value for the curve is 0.65. The volumetric water content at field capacity, at the permanent wilting point, the available water-holding capacity, and the management allowed deficit are determined from Equation 3 and presented in Table 13.4.

Table 13.4 Soil volumeteric water content at field capacity, the permanent wilting point, the available water-holding capacity and the management allowed deficit.

	Volumetric water content (%)	Pressure (cm)
Field capacity (FC)	24	300
Permanent wilting point(PWP)	15	1.5×10^3
Available water-holding capacity (AWHC)	9	
50 % management allowed deficit (MAD) MAD = FC- (AWHC/2)	19.5	

The management allowed deficit (MAD)[2] is the amount of available water that can be removed from the soil before the plant is stressed, as crops will be subjected to substantial water stress before the soil reaches the permanent wilting point. The allowable depletion varies depending on soil type, rooting depth, crops sensitivity to stress, time of season, characteristics of the irrigation system and other factors (Martin *et al.* 1990). In semi-arid and arid regions, a general rule is that the soil moisture deficit within the root zone should not fall below 50 % of the total available water-holding capacity of the soil (Keller and Bliesner 1990). This is as optimum plant growth typically occurs when soil moisture contents are close to field capacity, rather than over the complete range of moisture availability (Brady 1990). Using the management allowed deficit (MAD = field capacity minus half of the available water holding capacity) derived from the soil-water retention curve, the soil volumetric water content within the experimental plot should be above 19.5 % to avoid plant stress.

[2] The management allowed deficit (MAD) is also called the management allowed depletion, or the maximum allowable depletion.

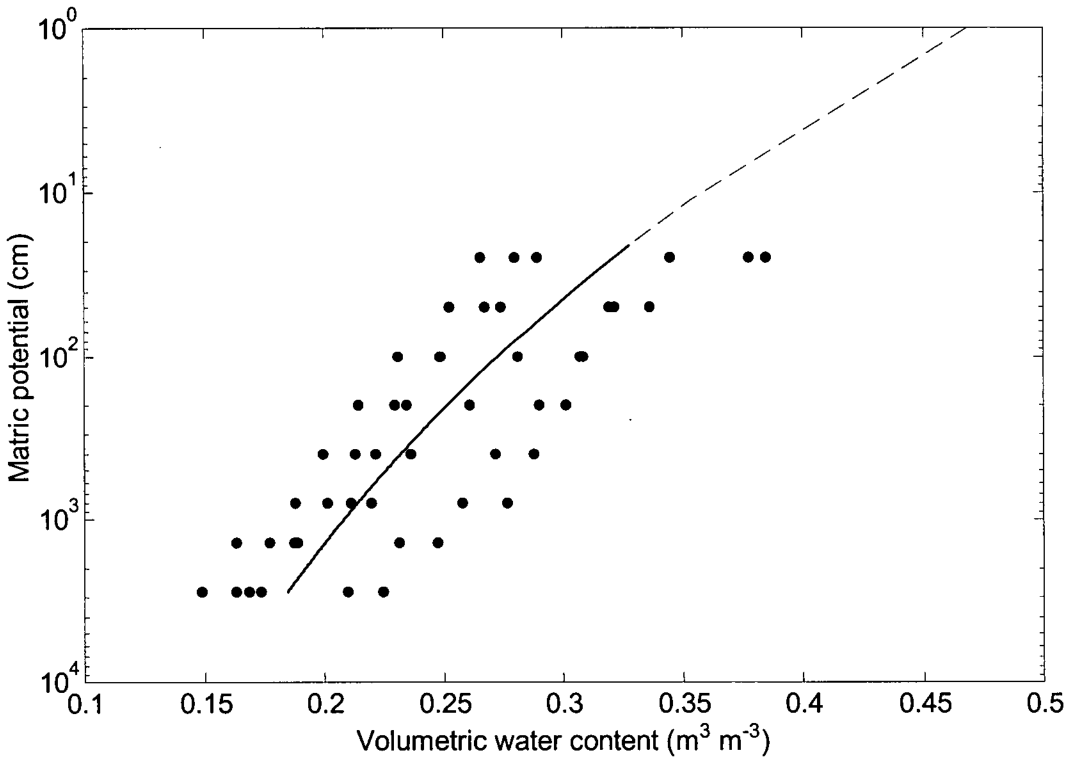

Figure 13.7 Soil-water retention curve for experimental plot. (Curve fitted by least squares method).

However, as Table 13.1 to Table 13.3 and Figure 13.1 to Figure 13.7 indicate, the soil volumetric water content was often much lower than 19.5% and generally only rose above this value for post-PM irrigation values. In fact, using Equation 3, the corresponding tension to the mean SVWC values indicates that the moisture content was below the permanent wilting point. As plants generally did not show major signs of water stress or experience mortality due to drought it is evident that a discrepancy exists.

The possibility exists that the matric potential curve is inaccurate as the samples were transported and thus the samples are not completely undisturbed. This would cause an error at the wetter end of the curve, such that a greater amount of pressure is required for the disturbed soil to reach field capacity. This is unlikely to be a factor as the pressure chosen to represent field capacity is 300 cm, typically the upper pressure range for field capacity. In addition, field capacity was only 24%, which is on the low side compared to typical values given for a sandy clay-loam soil (~30%) (Brady 1990).

The use of an equation derived from pressure plates to estimate the permanent wilting point may also introduce error, as pressure plates have decreased accuracy at high pressures. Jones *et al.* (1990) determined that over 90% of the soil samples placed on 1.5 MPa pressure plates did not equilibrate and observed that the sampled water potentials remained higher than the applied pressure would have indicated. This finding was independent of soil texture. Thus, it is likely that the use of an equation derived from pressure plates has overestimated the actual value of the permanent wilting point. This would result in the calculation of a lower SVWC at which plants become stressed.

Although disturbance of the core and the use of an equation derived from pressure plates to determine the permanent wilting point may have introduced a degree of error to the values, it is unlikely to cause any large changes in the values of permanent wilting point, MAD, or field capacity. The discrepancy between the soil-water retention curve and the field measured SVWC is more likely due to the soil depth that the matric potential curve represents and the depth at which the SVWC measurements occurred.

The matric potential curve is derived from a 3 cm high soil core, which represents the 0-3 cm depth profile. With depth, soil will increase in density and have a decline in pore sizes. In the field, the soil was observed to become more compact at depth and more clayey. The matric potential curve at depth will most likely also differ such that at depth plant roots will experience a greater SVWC at a greater pressure.

The SVWC measurements presented in Table 13.1 to Table 13.3 and Figure 13.1 to Figure 13.7 represent the average SVWC of a depth of 12 cm. However, although excavation of plant roots indicated that the majority of the roots were within a depth of 13-15 cm, a typical healthy plant also had a few roots that extended to much deeper depths and/or with a wide lateral extension. The maximum root depth of the eleven plants excavated was 39 cm, while the average maximum depth was 26 cm. The maximum lateral root expansion was 57 cm away from the plant stem and the average maximum lateral expansion was 39 cm. These deeper roots will thus be able to extract water at depth and thus the overall stress the plant is experiencing is likely overestimated by the matric potential corresponding to the SVWC measured over only a 12 cm depth.

The increase in soil density with depth made it very difficult to insert the probe rods to a depth of 20 cm. Thus 20 cm measurements were limited to one plant per line (instead of 3). For each plant at which measurements at 20 cm were made, measurements of the 12 cm depth were also made and graphed (Figure 13.8).

The equation for the calibration, determined via linear regression, is:

$$y = 0.88\,x + 6.2 \qquad (r^2 = 0.69)$$

Equation 4 Linear regression equation for calibration for 12cm to 20cm measurements.

where:

y = soil volumetric water content over 20 cm depth

x = soil volumetric water content over 12 cm depth

A transformation of the mean SVWC over a 12 cm depth to over a 20 cm depth (Figure 13.8) results in a considerable increase in the soil volumetric water content. With the transformation to 20 cm depth the post-PM irrigation SVWC for the morning-evening and evening-only regimes in both drip lines is at or slightly above field capacity. In fact, the morning-evening regime under LCDI irrigation has mean SVWC values above field capacity at both the AM measurement and the post-PM irrigation measurement. Although a high SVWC means that water is easily available to plants, water in excess of field capacity implies the soil is less aerated, which may detrimentally affect plant growth. Within the deficit irrigated lines, SVWC for the PM measurement drops below that of the 50% MAD value, thus indicating the plants were stressed. This was visually observed; plants under deficit irrigation lost leaf turgor between irrigation intervals, particularly in the later growth stages.

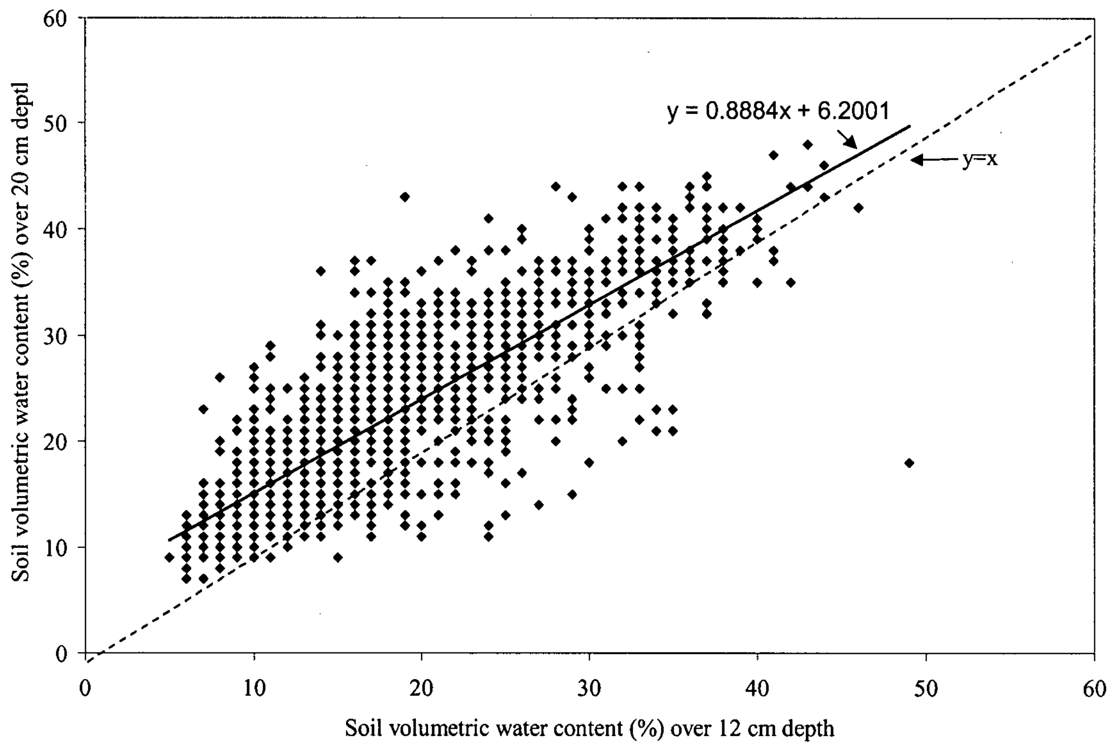

Figure 13.8 Linear regression of soil volumetric water content at 12 cm and 20 cm (n=1674).

Table 13.5 A comparison of the mean soil volumetric water content (%) over a 12 cm depth with the mean SVWC over a 20 cm depth for each irrigation method.

	Mean soil volumetric water content (%) of LCDI					
Measurement time	Deficit		Morning-Evening		Evening-Only	
	12 cm depth	20 cm depth	12 cm depth	20 cm depth	12 cm depth	20 cm depth
AM	14.3	**19.0**	21.2	**26.0**	17.5	**21.6**
PM	10.2	**15.2**	18.0	**22.8**	13.6	**18.1**
Post PM irrigation	18.2	**22.5**	24.6	**29.4**	21.1	**24.8**
Mean soil volumetric water content (%) of Western drip						
Measurement time	Deficit		Morning-Evening		Evening-Only	
	12 cm depth	20 cm depth	12 cm depth	20 cm depth	12 cm depth	20 cm depth
AM	14.8	**19.4**	18.4	**23.2**	17.8	**21.9**
PM	11.0	**15.9**	15.3	**20.2**	14.1	**18.6**
Post PM irrigation	17.8	**22.2**	20.0	**24.8**	21.3	**25.0**
Mean soil volumetric water content (%) of Hand-Watered						
Measurement time	Deficit		Morning-Evening		Evening-Only	
	12 cm depth	20 cm depth	12 cm depth	20 cm depth	12 cm depth	20 cm depth
AM	14.6	**19.2**	14.6	**19.5**	17.5	**21.6**
PM	11.3	**16.2**	10.8	**15.7**	13.4	**18.0**
Post PM irrigation	18.1	**22.5**	15.4	**20.2**	20.6	**24.3**

13.4. Summary: Soil volumetric water content

Differences between irrigation methods were present in the morning-evening irrigation regime and the deficit irrigation regime, but not in the evening-only irrigation regime. Differences in the SVWC between irrigation methods are small under deficit irrigation, and generally the lines have similar mean values and similar fluctuations through time. In contrast, under the morning-evening irrigation regime differences between the irrigation methods are considerable. Hand-watered irrigation results in significantly lower mean volumetric water contents. This may be due to a combination of the mechanism of water application and crop growth. The lack of a difference under the evening only irrigation regime may be linked to the water volumes being applied. At greater volumes of water application per irrigation event it is more likely that differences in the SVWC over a 12 cm radius become less noticeable.

Deficit irrigation resulted in significantly lower SVWC than full irrigation in both drip methods. However, under hand-watering, deficit irrigated lines were only significantly less than the evening-only irrigation regime. This suggests that the SVWC of the hand- watered morning-evening line is uncharacteristically low.

A soil-water retention curve was determined from six soil cores. Based on the retention curve, it appears that the measured SVWC's are low, often below the permanent wilting point. Field based observations do not support this, as plants were not severely affected by wilt, nor did they die of drought. Calibration of the SVWC measurements taken at 12 cm to a 20 cm depth indicates that the SVWC at 20 cm are more closely associated with stress levels that the plants would have experienced, and were typically within the MAD. Full irrigation volumes with drip irrigation resulted in SVWC's close to field capacity. In the morning-evening regime of LCDI, SVWC's were greater than field capacity, with an expected reduction in soil aeration. Deficit irrigation resulted in SVWC closer to the lower limit of the MAD.

No consistent trend in the differences in the SVWC of the three irrigation methods was determined. Increased replications and trials would provide greater insight into potential differences.

14. BIOMASS

Biological parameters were measured for all cauliflower plants at the time of harvest. The median results for each line (sum of replicate lines a and b) are presented in Table 14.1 and the cumulative yields of crop residue, cauliflower mass, and aboveground (AG) biomass for each line are presented in Table 14.2.

Table 14.1 Summary of median biological parameters of all irrigation lines

Line #	n[1]	Plant width (cm)	Plant height (cm)	Root depth	# of leaves	Crop residue[2] (g)	Cauliflower mass (g)	Cauli-flower width (cm)	Above-ground biomass[3] (g)	Root mass (g)	Mean # of days[5]
D1	36	75	46	21	21	822	902	17.5	1627	48	83
D2	33	71	46	21	23	767	636	15	1274	55	84
D3	36	73	47	20	23	923	763	16.5	1782	73	85
D4	39	71	46	19	23	870	683	15.5	1485	68	86
D5	40	77	47	20	22	911	865	17	1581	68	82
D6	35	79	51	22	24	1000	630	15.5	1339	79	83
HW 1	40	86	47	26	24	1148	1193	17.75	2316	82	79
HW 2	40	86	49	21	23	1132	894	17	1971	78	85
HW 3 and HW 4[4]	77	76	43	20	22	870	680	15	1566	63	86

[1] Plants with disease or replacement plants were not included in analysis

[2] Crop residue refers to all green material (leaves + stem), but does not include cauliflower mass

[3] Aboveground biomass = crop residue + cauliflower mass

[4] Values for HW 3 and HW 4 were combined; these were replicate lines with no significant differences between them

[5] Mean # of days to harvestable state

Table 14.2 Total cumulative yield of crop residue, cauliflower mass, and biomass for each line.

Irrigation method (regime)	Line #	Crop Residue (kg) ± st. dev.	Cauliflower mass (kg) ± st. dev.	Aboveground biomass (kg) ± st. dev.
LCDI (D) (n=40)	D1	30.5 ± 0.3	32.2 ± 0.4	56.2 ± 0.6
Western (D) (n=40)	D2	30.6 ± 0.4	24.7 ± 0.5	49.7 ± 0.8
LCDI (ME) (n=40)	D3	37.1 ± 0.4	29.8 ± 0.4	63.6 ± 0.7
Western (ME) (n=40)	D4	34.9 ± 0.4	27.4 ± 0.4	57.5 ± 0.7
LCDI (EO) (n=40)	D5	36.2 ±0.3	35.1 ± 0.3	64.9 ± 0.5
Western (EO) (n=40)	D6	40.8 ± 0.5	24.2 ± 0.4	59.0 ± 0.9
Hand watered (ME) (n=40)	HW 1	46.2 ± 0.2	41.1 ± 0.4	87.3 ± 0.6
Hand watered (EO) (n=40)	HW 2	46.2 ± 0.4	35.1 ± 0.5	81.3 ± 0.8
Hand watered (D) (n=40)	HW 3/4	36.1 ± 0.2	28.2 ± 0.4	64.3 ± 0.6

Variables used as indicators of performance were crop residue, cauliflower mass, aboveground biomass, root mass, and the number of days to harvest. In Nepali agriculture, all above ground parts of the cauliflower plant are harvested; the fruit itself is either sold or consumed, the inner leaves are often eaten raw or dried for later use in a curry, while the outer leaves are fed to livestock. For these reasons crop residue, cauliflower mass, and aboveground biomass are all appropriate indicators of performance. Root mass gives an indication of root development, although difficulties in attaining a uniform condition to weigh the roots makes this the least reliable of the indicators. The number of days to maturity is an important indicator as plants that reach maturity earlier require less water and thus save farmers water and the opportunity cost of water. A greater value for the first four indicators and a smaller value for the number of days to harvest indicates a better system performance. A final assessment of each irrigation system will be made based on the mass of cauliflower produced, as this is ultimately the indicator that farmer's value most.

Significant differences were examined between irrigation systems within the three watering regimes (deficit irrigation (D), morning-evening (ME), and evening only (EO)) (Table 14.3 - Table 14.5). As described earlier, plants under deficit irrigation received 50 % of the estimated plant water requirement. Plants under the ME and EO regimes received the full estimated plant water needs as determined by Equation 1[3]. The two groups differ in the timing, and thus daily volumes of water applications.

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[3] $W = (0.4983 \times D^2 \times PF \times ET_o)/ EF$

where W = daily water requirement per plant , PF = plant factor (=1.0), D = Diameter of plant canopy (ft^2) ET_o = potential evapotranspirtation (inches/day), ET = irrigation efficiency

14.1.1. Deficit irrigation: Low cost drip irrigation versus western drip irrigation versus hand-watered

Under deficit irrigation, no significant difference existed between the different irrigation methods in crop residue production or aboveground biomass production. In contrast, cauliflower mass was significantly greater in LCDI than in both Western and hand watered irrigation methods (Table 14.3 and Figure 14.1). No difference in cauliflower yield existed between Western drip and hand-watered irrigation methods. Hand watered lines had a significantly greater root mass than LCDI, yet no significant difference to Western drip. The average number of days to maturity was significantly less for LCDI than for hand-watered (Table 14.3).

Table 14.3 Deficit irrigation: LCDI vs. Western drip lines vs. hand-watered (HW): Comparison of performance crop indicators.

Irrigation method comparison	Crop Residue (g)	Cauliflower mass (g)	Aboveground biomass (g)	Root mass (g)	# of days to maturity
LCDI vs Western	NS	LCDI > Western	NS	NS	NS
LCDI vs HW	NS	LCDI > HW	NS	HW > LCDI	LCDI < HW
Western vs HW	NS	NS	NS	NS	NS

NS = no significant difference, ($\alpha<0.05$) LCDI = low cost drip irrigation, HW = hand watered.

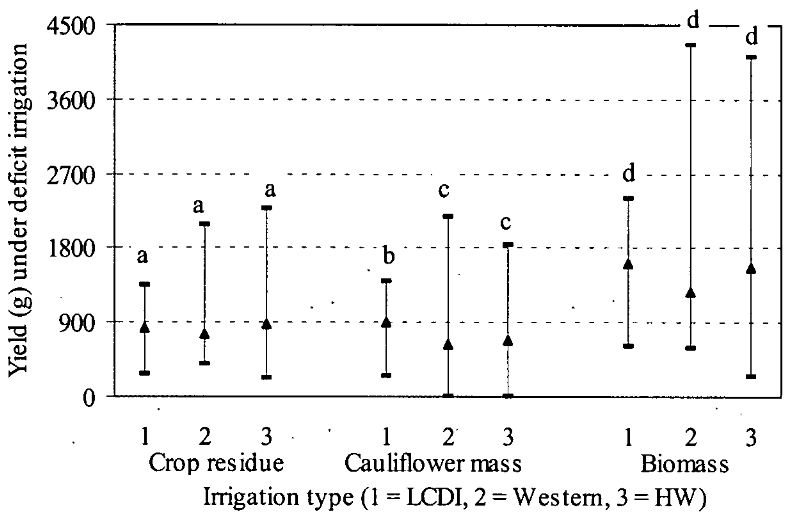


Figure 14.1 Significant differences in crop residue, cauliflower mass, and aboveground biomass between different irrigation methods under deficit irrigation (min, max, median (▲)), Kruskal-Wallis, $\alpha < 0.05$). Significant differences within a group indicated by different letters.

LCDI had the lowest variability among the three irrigation methods. The maximum AG biomass (4263 g) occurred in the Western drip irrigated line, although the median AG biomass was only 1274. In fact, this was the maximum AG biomass recorded for the entire experiment. It is difficult to ascertain exact causes of the variability in crop yield as it is influenced by many factors, however the poor emission uniformity of the individual emitters, seedling variability, and inherent variability within the soil are all likely contributing, in varying degrees, to the overall variability.

Under deficit irrigation LCDI performed the best of the three irrigation methods, most importantly producing the greatest mean amounts of cauliflower yield, and also AG biomass. Although differences in SVWC were significant between the irrigation methods at the PM and post-PM irrigation regime, the magnitude of the differences were small. It is thus unlikely that differences in SVWC caused cauliflower yield under LCDI to be significantly greater. Differences in yield between the irrigation methods are thus likely due to inherent system variability.

14.1.2. Morning-evening irrigation: Low cost drip irrigation versus Western drip versus hand-watered

Under the morning-evening regime, LCDI and Western drip irrigation performed similarly for all five indicators. In contrast, the hand-watered regime outperformed both drip methods for all variables (Table 14.4). Similarly, the hand-watered regime had the lowest variability of the three methods (Figure 14.2).

Table 14.4 Morning-evening irrigation regime: LCDI vs. Western drip lines vs. hand-watered (HW): Comparison of crop performance indicators.

Irrigation regime comparison	Crop residue (g)	Cauliflower mass (g)	Above-ground biomass (g)	Root mass (g)	# of days to maturity
LCDI vs Western	NS	NS	NS	NS	NS
LCDI vs HW	HW >LCDI	HW >LCDI	HW >LCDI	HW >LCDI	HW< LCDI
Western vs HW	HW > Western	HW > Western	HW > Western	HW > Western	HW < Western

NS = no significant difference, (α<0.05) LCDI = low cost drip irrigation, HW = hand watered.

The observed result that hand watering performed the best of the three irrigation methods was unexpected. It does appear to be more related to the SVWC of the irrigation lines. Hand-watered lines had significantly lower SVWC than drip lines, yet significantly greater yields. If the SVWC's calibrated to a 20 cm depth are considered, the SVWC is close to, or slightly greater than, field capacity for the drip lines. This may imply that the plants were receiving too much water, which can also cause water stress. Metabolic activity is required to maintain the root membranes through which water passes from the soil to the root. Irrigation cools the soil and decreases the oxygen content of the soil; both of these factors will reduce root respiration rates, thereby decreasing the metabolic activity of the roots. Increased root resistance to water flow will result which can create a water stress situation (Campbell and Turner 1990).

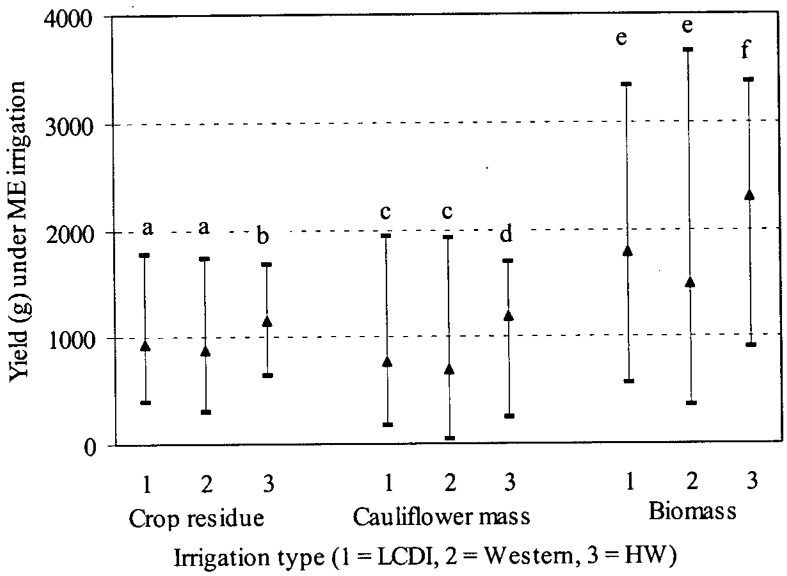


Figure 14.2 Significant differences in crop residue, cauliflower mass, and aboveground biomass between different irrigation methods under ME irrigation (min, max, median (▲)), Kruskal-Wallis, $\alpha < 0.05$). Significant differences within a group indicated by different letters.

14.1.3. Evening-only irrigation: Low cost drip irrigation versus Western drip irrigation versus hand watered

In the evening-only irrigation regime, hand-watered lines do not outperform the drip line as in the morning-evening regime. Results vary by indicator. No difference in root mass was observed between the three irrigation methods. Biomass was significantly greater in hand-watered lines than both LCDI and Western drip irrigation. Crop residue was significantly greater in hand-watered lines than LCDI only. Cauliflower yield was significantly less in Western drip than both LCDI ($\alpha < 0.05$) and hand – watered irrigation methods ($\alpha = 0.051$) (Table 14.5 and Figure 14.3). No differences in cauliflower mass were observed between LCDI and hand-watered methods, and thus both systems worked equally well under this irrigation regime. As the SVWC was not significantly different between the irrigation methods, differences in AG biomass indicators cannot be attributed to SVWC and are likely more related to variability in seedling quality and micro-environments within the soil.

Table 14.5 Evening-only irrigation regime: LCDI vs. Western drip lines vs. hand-watered (HW): Comparison of crop performance indicators.

Irrigation regime comparison	Crop residue (g)	Cauliflower mass (g)	Aboveground biomass (g)	Root mass (g)	# of days to maturity
LCDI vs Western	NS	LCDI > Western	NS	NS	NS
LCDI vs HW	HW >LCDI	NS	HW >LCDI	NS	HW< LCDI
Western vs HW	NS	NS*	HW > Western	NS	NS

NS = no significant difference, (Kruskal-Wallis, $\alpha<0.05$) LCDI = low cost drip irrigation, HW = hand watered.
* Significant at $\alpha = 0.051$

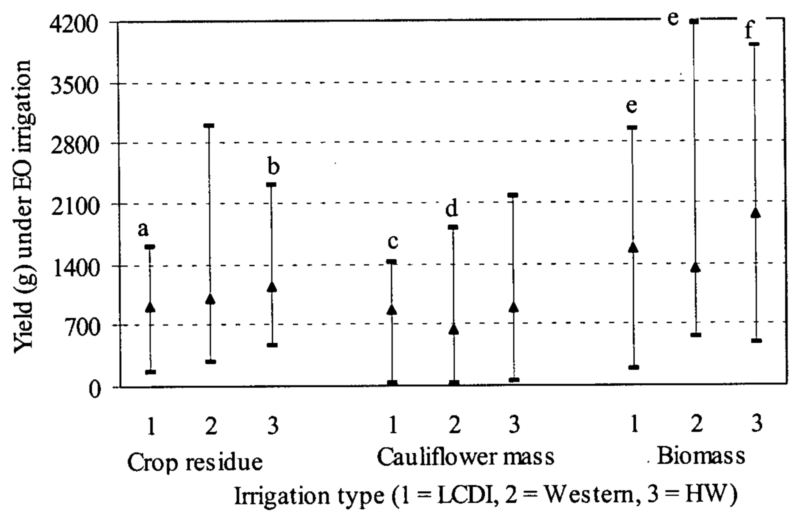


Figure 14.3 Significant differences in crop residue, cauliflower mass, and aboveground biomass between different irrigation methods under EO irrigation (min, max, median (▲)), Kruskal-Wallis, $\alpha < 0.05$). Significant differences within a group indicated by different letters.

14.1.4. Summary: comparison between irrigation methods within an irrigation regime.

Based on cauliflower yields, LCDI performed the best of the three irrigation methods operating under deficit irrigation. Under the morning-evening schedule, the hand watering method had the best performance, while under the evening-only regime, both LCDI and hand-watered methods performed equally well. In none of the regimes tested did Western drip irrigation result in better performance than the other two irrigation methods. The SVWC likely did not significantly affect the performance of AG biomass indicators under either deficit irrigation or the evening-only irrigation regime.

Under the morning-evening irrigation regime, significant differences in the SVWC appear to have influenced the performance of AG biomass indicators. The hand-watered line had the lowest SVWC and the greatest yield, thus it is possible that under the drip irrigation the frequent applications of the morning-evening regimes resulted in water stress due to insufficient aeration.

The performance of the irrigation methods within an irrigation regime may also be ranked based on the cumulative yield of crop residue, cauliflower mass, and AG biomass for the respective lines (Table 14.6).

Table 14.6 Ranking of irrigation methods within an irrigation regime based on total yields.

Rank	Irrigation regime	Crop residue (total yield (kg))	Cauliflower mass (total yield (kg))	Aboveground biomass (total yield (kg))
1	*Deficit*	HW (36.1)	LCDI (32.2)	HW (64.3)
2		W ~ LCDI (~30.5)	HW (28.2)	LCDI (56.2)
3			W (24.7)	W (64.3)
1	*ME*	HW (46.2)	HW (41.4)	HW (87.3)
2		LCDI (37.1)	LCDI (29.8)	LCDI (63.6)
3		W (34.9)	W (27.4)	W (57.5)
1	*EO*	HW (46.2)	HW = LCDI (35.1)	HW (81.3)
2		W (40.8)	W (24.2)	LCDI (64.9)
3		LCDI (36.2)		W (59.0)

The greatest difference in the total cauliflower yield produced between the three irrigation methods was in the ME irrigation regime in which the hand-watered line produced 14 kg more cauliflower than the Western drip line. The hand-watered irrigation regime also consistently had a higher mass of total crop residue production than either of the drip methods.

14.1.5. Differences between water regimes within an irrigation method.

In comparing the differences between irrigation regimes within a given irrigation method (e.g. LCDI or Western or HW) it was expected that regardless of irrigation method significant differences would occur between deficit irrigated lines receiving only 50 % of recommended daily water amount and those lines receiving the full quota of required water. No significant differences were expected between lines watered either by the ME or EO regimes within a given irrigation method as the soil is a sandy-clay loam soil, and thus is not as sensitive to irrigation frequency as would be a sandy soil.

Low cost drip irrigation: deficit versus morning-evening versus evening only

In LCDI, crop residue and root mass were significantly less under the deficit irrigation regime than under either the ME or the EO irrigation regimes. However, there was no significant difference in either cauliflower mass or AG biomass between deficit, ME, and EO irrigation regimes (Table 14.7). Scheduling differences had no significant effect on performance other than on the number of days to maturity. Plants in the ME line reached maturity slower than plants in both the EO and deficit lines (Table 14.7 and Figure 14.4).

Table 14.7 Significant differences in crop performance indicators between different watering regimes for LCDI lines.

Irrigation regime comparison	Crop residue (g)	Cauliflower mass (g)	Aboveground biomass (g)	Root mass (g)	# of days to maturity
Deficit vs ME (D1 vs D3)	ME > Deficit	NS	NS	ME > Deficit	ME > Deficit
Deficit vs EO (D1 vs D5)	EO > Deficit	NS	NS	EO > Deficit	NS
ME vs EO (D3 vs D5)	NS	NS	NS	NS	ME > EO

NS = no significant difference, (Kruskal, Wallis, α<0.05) ME = morning-evening regime, EO = evening only regime

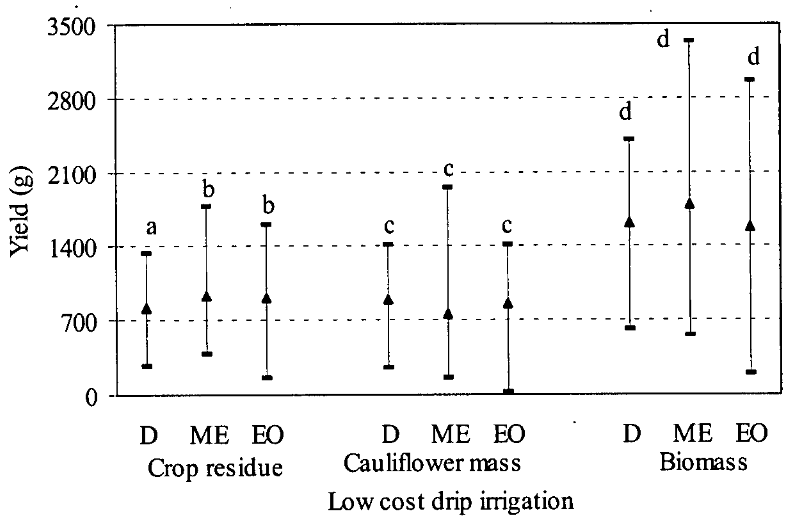


Figure 14.4 Comparison of min, max, and median (▲) crop residue, cauliflower mass, and aboveground biomass between different LCDI lines. Significant difference indicated by differences in letters within a group. Kruskal-Wallis, α <0.05.

The maximum absolute values for crop residue, cauliflower mass, and AG biomass were attained in the ME regime, which was also characterized by high variability. Deficit irrigation had the least variability for the performance indicators.

Western drip irrigation: deficit versus morning-evening versus evening only

Similar to LCDI, in Western drip lines no significant difference was observed ($\alpha < 0.05$) in cauliflower mass, AG biomass, root mass, or the number of days to maturity between the three irrigation regimes. The EO line was characterized by high crop residue production (and comparatively low cauliflower production) resulting in significantly greater crop residue than both deficit and ME regimes (Table 14.8). The degree of variability varied with the indicator being measured. No particular irrigation regime appears to be more variable for the indicators (Figure 14.5), nor does any particular irrigation regime result in a statistically significant better performance in the Western drip lines.

Table 14.8 Significant differences in crop performance indicators between different watering regimes for Western drip lines.

Irrigation regime comparison	Crop residue (g)	Cauliflower mass (g)	Aboveground biomass (g)	Root mass (g)	# of days to maturity
Deficit vs ME (D2 vs D4)	NS	NS	NS	NS	NS
Deficit vs EO (D2 vs D6)	EO > Deficit	NS	NS	NS	NS
ME vs EO (D4 vs D6)	EO > ME	NS	NS	NS	NS

NS = no significant difference, (Kruskal-Wallis, α<0.05) ME = morning-evening regime, EO = evening only regime, D = deficit regime

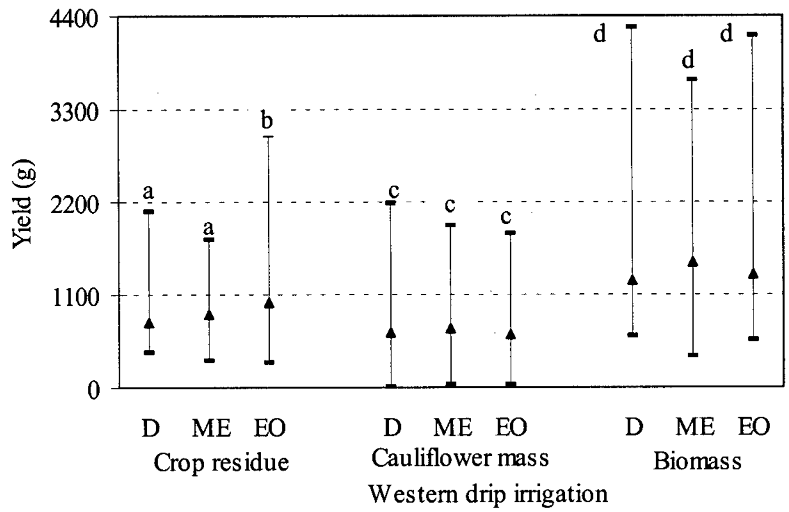


Figure 14.5 Comparison of min, max, and median (▲) crop residue, cauliflower mass, and aboveground biomass between different Western drip lines. Significant difference indicated by differences in letters within a group. Kruskal-Wallis, α <0.05

Hand watered irrigation: deficit versus morning-evening versus evening only

Within the hand watered regime, crop residue and root mass were also significantly less under deficit irrigation than under ME and EO regimes. In contrast to the drip irrigation methods, in the hand-watered lines a statistically significant decline occurs in cauliflower mass with deficit irrigation (ME > D) and in the AG biomass. Again, irrigation schedule between ME and EO did not have and apparent affect on performance indicators except the number of days to maturity (Table 14.9).

Table 14.9 Significant differences in crop performance indicators between different watering regimes for hand watered lines.

Irrigation regime comparison	Crop residue (g)	Cauliflower mass (g)	Aboveground biomass (g)	Root mass (g)	# of days to maturity
Deficit vs ME (HW 4 vs HW 1)	ME > Deficit	ME > Deficit	ME > Deficit	ME > Deficit	Deficit > ME
Deficit vs EO (HW 4 vs HW 2)	EO > Deficit	NS	EO > Deficit	EO > Deficit	NS
ME vs EO (HW 1 vs HW 2)	NS	NS	NS	NS	EO > ME

NS = no significant difference, (Kruskal-Wallis, $\alpha<0.05$) ME = morning-evening regime, EO = evening only regime

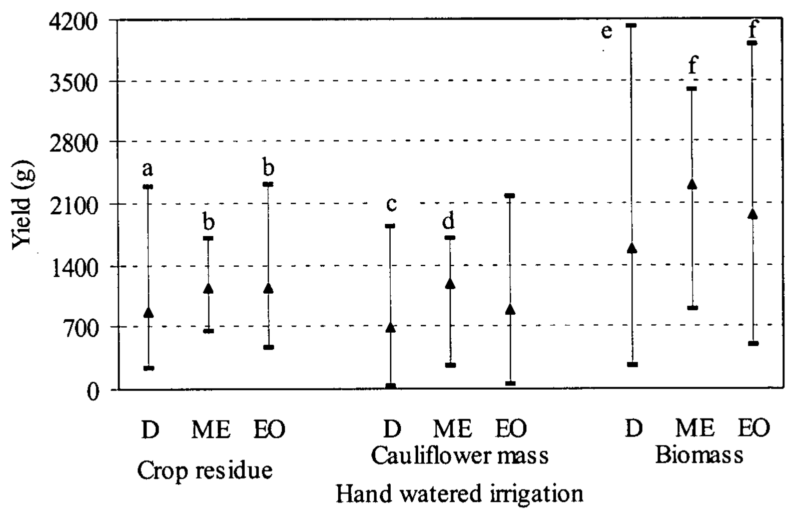


Figure 14.6 Comparison of min, max, and median (▲) crop residue, cauliflower mass, and aboveground biomass between different LCDI lines. Significant difference indicated by differences in letters within a group. Kruskal-Wallis, $\alpha < 0.05$

Among the three irrigation regimes, variability was least in the ME irrigation lines. The ME regime also had the greatest mean production of crop residue, thus appears to be best suited for hand watering.

14.1.6. Effect of SVWC on plant performance

In both drip methods, the SVWC was significantly less in the deficit regime than in the ME or the EO regime. This did not appear to affect either AG biomass production or cauliflower production, as differences in these indicators between irrigation regimes were insignificant. However, SVWC did appear to have an affect on the production of crop residue. Crop residue was either significantly reduced or exhibited a trend towards lower production (Table 14.10) under the lower SVWC of deficit irrigation for both drip methods. The significantly lower production of crop residue under deficit irrigation suggests that plants may preferentially partition resources to the cauliflower fruit, at the expense of leaves and green matter.

Under hand watering, SVWC did not show a similar affect on plant performance. The ME irrigation regime, which had a significantly lower SVWC than both the deficit and EO regime, had better plant performance than the deficit regime and no statistical difference to the EO regime.

Given the conflicting results between the drip irrigation methods and the hand-watered methods the effect of SVWC on growth parameters cannot be conclusively stated. Additional trials and replicates would provide a more definitive answer.

Table 14.10 Ranking of irrigation regimes for each irrigation method based on total yields.

Irrigation method	Crop residue (total yield (kg))	Cauliflower mass (total yield (kg))	Aboveground Biomass (total yield (kg))	Rank
LCDI	ME (37.1)	EO (35.1)	EO (64.9)	1
LCDI	EO (36.2)	D (32.2)	ME (63.6)	2
LCDI	D (30.5)	ME (29.8)	D (56.2)	3
Western	EO (40.8)	ME (27.3)	EO (59.0)	1
Western	ME (35.0)	D (24.7)	ME (57.5)	2
Western	D (30.6)	EO (24.2)	D (49.7)	3
Hand watered	ME (46.2)	ME (41.1)	ME (87.3)	1
Hand watered	EO (46.2)	EO (35.1)	EO (81.3)	2
Hand watered	D (36.1)	D (28.2)	D (64.3)	3

14.1.7. Summary: comparison between irrigation regimes within an irrigation method.

Based on the total cumulative cauliflower yield of each of the LCDI lines (Table 14.10), the EO regime performed the best under LCDI. However, the range in the total cauliflower yield values is small. This indicates that cauliflower yield under LCDI was not sensitive to the irrigation regime used.

For Western irrigated lines, no statistical difference was observed in either cauliflower mass or AG biomass. Crop residues were significantly greater under the EO regime. Based on the cumulative cauliflower mass the ME irrigation line performed best, but similar to LCDI the range in cauliflower mass between the irrigation regimes was small, only 3 kg. This is equivalent to a 75 g per plant difference between ME and deficit irrigated lines (Table 14.10). Thus, no irrigation regime appears to have been particularly advantageous.

For hand-watered lines, although no statistical difference was observed between the ME and EO regimes, the ME regime produced a higher total cauliflower yield than the EO regime and thus can be considered to have the best performance (Table 14.10). In contrast to the drip lines, where the range in the total cauliflower yields attained was small (~3-6 kg), under hand watering the range was 12.9 kg. This is equivalent to a 322 g per plant difference in cauliflower mass between the poorest performing regime (deficit irrigation) and the best performing regime (ME irrigation). Thus, the cauliflower yield obtained by hand-watering appears to be much more sensitive to the irrigation regime, particularly the water volume applied, than drip irrigation methods.

14.1.8. The effects of deficit irrigation

In examining trends between deficit irrigated lines versus lines receiving full estimated daily water requirements (regardless of irrigation method) it should be noted that in both the LCDI and the hand-watered methods, root mass is significantly less in deficit irrigated lines. This corresponds to findings by Xiao and Subbarao (2000), who observed that root length density was significantly higher in excessive irrigation regimes than in deficit irrigation regimes. This is because soil moisture is a major factor in root growth rate and distribution. In contrast, no significant difference in root mass between deficit and full irrigation was determined for Western drip lines, although a trend of lower root mass was observed for the deficit irrigation regime.

A difference in the total yield between lines under deficit irrigation and those under EO or ME irrigation (full water requirements) was observed for each of the irrigation regimes (Table 14.11). Deficit irrigated lines had declines of 12% - 26% in the total crop residue and AG biomass produced per line when compared with production under lines receiving full irrigation requirements. The percent decline in the total cauliflower mass produced under deficit irrigation versus full irrigation was greatest in the hand-watered irrigation method. In drip irrigation, declines in cauliflower yield under deficit irrigation are less and in two instances positive (Table 14.11). Positive values may indicate that cauliflower yields within the lines receiving full water requirements are depressed rather than deficit irrigation outperforming the full irrigation lines.

Table 14.11 The percent change in total yield in deficit irrigation versus full irrigation regimes.

Irrigation Method	Irrigation regime comparison	% change in:		
		Crop residue	Cauliflower	Aboveground biomass
LCDI	D vs. ME	-18	+ 8	-12
	D vs EO	-16	-8	-13
Western	D vs ME	-12	-10	-14
	D vs EO	-25	+ 2	-16
Hand-watered	D vs ME	-22	-31	-26
	D vs EO	-22	-20	-21

D = deficit regime, ME = morning-evening regime, EO = evening only regime

The comparatively large reduction in the total yield of cauliflower produced under deficit irrigation for hand-watered irrigation implies that under situations of water scarcity hand-watering is not as attractive as drip irrigation which had lower reductions in yield under deficit irrigation.

15. ECONOMICS OF IRRIGATION SYSTEMS

Farmers are interested in the cultivation of an additional crop not only for food security reasons but also for economic reasons. Field experiences with LCDI in the Tanahun district of Nepal have indicated that farmers typically sell a portion of their produce for cash sales, and that these sources of cash are perceived as an important benefit of growing an additional crop. The economics were calculated assuming each irrigation method was operating on a ¼ ropani field size (127 m^2) growing 320 plants. Data used in the calculations was determined from the experimental trials and adjusted to 320 plants.

Costs were subdivided into capital and variable costs. As expected, capital costs were greatest for the Western drip system (Table 15.1), since emitters are not available in Nepal and foreign exchange rates are punitive (in 2000 $1 Cdn = 47.7 Nepali rupees (NRp)). It was assumed that all pipes used in the Western irrigation system would be purchased in Nepal, as these are readily available and less expensive. It was also assumed that non-pressure compensating drip emitters would be used to further reduce the cost of a Western drip system. Western drip systems are still 16 times more expensive in capital cost than LCDI. It must be remembered that the Western drip system used in this experiment had a simplified design in comparison to a conventional drip set-up found in developed countries, which typically include a pressurized water source, complex filtration system, and a much greater degree of automation.

Most farmers currently using LCDI in Nepal utilize a 50 L drum to store water, rather than the 100 L drum used in this experiment. This would reduce their capital costs by approximately an additional 200 NRp. Irrigating by hand had the lowest capital cost as only a bucket and something to scoop water is required to irrigate, both of which are inexpensive.

Variable costs include fertilizers, pesticides, seedlings, and labour. Labour accounts for approximately 65% - 70% of the variable costs and 38%, 7 %, and 63% of the total cost for LCDI, Western drip, and hand-watered irrigation methods respectively. Labour includes time spent preparing the land, weeding, irrigating, shifting laterals, and fetching water (for a detailed breakdown of labour costs see Appendix 10). The cost of labour was assumed to be 75 NRp per 10 hour day. This values family labour at only 75% of a paid labourer, who at current rates typically earns 100 NRp per day (Kennedy and Dunlop 1989, Shrestha 1999). Fetching water dominates labour costs, comprising between 65-90% of the total labour costs. Time required to fetch water is based on a watershed average of a 22-minute roundtrip (Merz *et al.* 1999). It was assumed that 25 L of water is carried per trip. Labour costs are greatest for hand-watering due to the time required to water each individual plant and refill the water buckets. The

Table 15.1 Economics for three different irrigation methods on a 127 m2 field at minimum price (NRp/kg) for cauliflower.

Costs (NRp)	LCDI	Western	Hand-watered
Capital costs			
Drip irrigation system	900	14300	-
100 L drum	440	440	-
Bucket and scoop	-	-	300
Variable costs			
Fertilizer and pesticides	265	265	265
Seedlings	320	320	320
Labour costs: Fetching water	975	975	975
Labour costs: other activities	225	100	563
Total costs (Season 1, Crop 1)	3125	16400	2423
Gross income			
Cauliflower sales (15 Rp/kg)	3840	3840	3840
Net income (Labour costs included)	715	-11485	1417
Net income (Labour costs excluded)	1915	-10410	3255
# of crops needed until capital costs are paid off (labour costs included)	1.9	> 20	1
Net income at first season after payoff (labour costs included)	2055	Na	1717

labour costs of LCDI are greater than Western drip irrigation due the time required to shift the LCDI lines.

The amount of cauliflower produced was based on the average yield derived from all lines within the experimental plot. It was assumed that the cauliflower was grown with the full water requirement, that all cauliflower produced was sold, and that the selling rate was 15 Rp/kg. The price for cauliflower is at a maximum in October (35 Rp/kg) and declines as the season progresses to 15 Rp/kg by mid December, to its low of 10 Rp/kg in early January. At a rate of 15 NRp/kg, with the inclusion of labour costs, growing cauliflower will result in a positive net income for both the LCDI and the hand-watered irrigation methods, but not for the Western drip irrigation (Table 15.1). Even at the maximum price of cauliflower (35 NRp per kg), western drip irrigation does not generate a cash profit. Although farm labour was included in the analysis, farmers typically do not explicitly calculate the cost of family labour, in part because family members may not have access to paid work (e.g. women, children).

This rough economic analysis indicates that after one cauliflower crop, a farmer will generate more profit by hand-watering the plants than by using low-cost drip irrigation because of the higher capital cost of the LCDI system. This leads to the question of "why would (and do) farmers choose LCDI instead of watering by hand?" First, this analysis assigns an equivalent economic value to all labour activities. Thus, the time spend in a stooped position and scooping water onto 320 plants is considered equivalent economically to turning on an irrigation system and shifting irrigation lines. However, as the former activity is physically more demanding than the latter it should have a higher economic cost associated with it, which would decrease the profitability of hand watering over LCDI. Secondly, expansion to a larger field cost will result in a proportionately greater increase in labour costs for hand watering than for LCDI, thus reducing the long-term benefits of a hand watering. Furthermore, once the capital cost of a LCDI system is paid off (which can be within 2 crops depending on yield and sale price), LCDI generates more profit than hand watering due to lower labour costs.

Watering by hand requires a methodological and diligent application, which is easy to apply in a research setting. However, the same trials run by two farmers in the watershed indicated that irrigation of hand-watered lines was less consistent than the irrigation of drip lines. As a result, yields were better under drip irrigation than hand-watered (unpublished data). One farmer commented that LCDI was better since "it is very easy, one simply opens the tap and then one can go on doing other tasks". They also noted that carrying the water was the most labour intensive part of the experiment. Farmers in the Tanahun district working with IDE expressed similar sentiments. One woman described how watering her ¼ ropani plot with a hose used to take her 1-2 hours, now she only spends a total of 20 minutes using LCDI. This view was common to most farmers who were informally interviewed by IDE (n ~ 50) in the Tanahun district.

The common irrigation practices for cauliflower is either by furrow irrigation, or by hose, or simply by tossing waste household water onto plants in a kitchen garden. No farmers use a scoop system. A farmer who wanted to use a scoop to hand-water would need to know the correct amount of water to apply and have a means of estimating this amount. This information would need to be distributed through extension activities. Farmers who choose to use a watering can rather than a scoop would be unable to regulate how much water each plant received, resulting in a more variable water distribution.

The fact that farmers do not commonly irrigate each plant carefully by hand is likely a combination of the physical demands, the diligent and methodological approach required, and the lack of knowledge that, for cauliflower, this irrigation method appears to produce yields at least as good as drip irrigation.

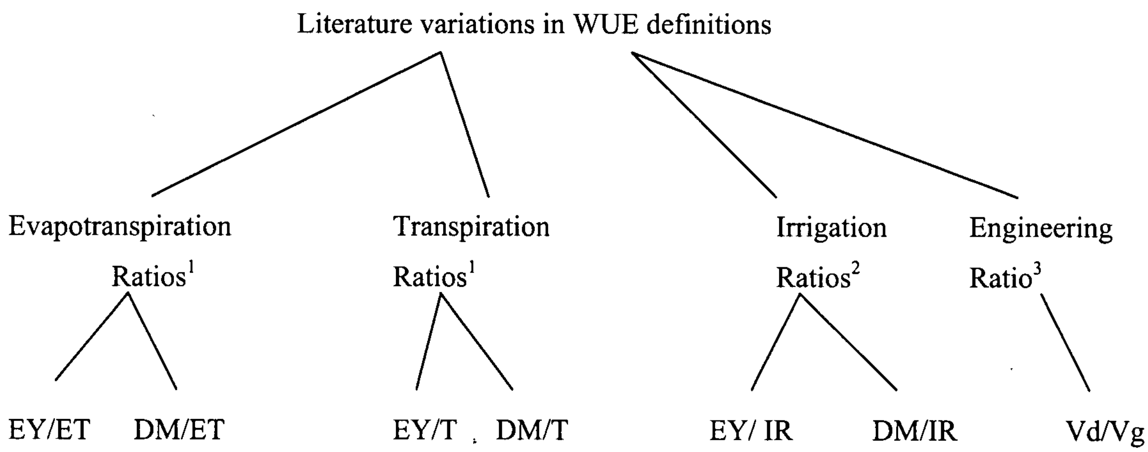
This raises a final issue. Although cauliflower yields under this trial were equivalent for both LCDI and hand-watered, different crops will likely differ in this regard. A field trial comparing a LCDI system developed by Chapin Watermatics Inc. and hand watering indicated higher yields for tomatoes, Swiss chard, and zucchini for the LCDI, but no difference in yield for cabbage, which, like cauliflower, is also a cole crop (Chapin Watermatics Inc, 1997). Additional trials are needed to confirm the whether LCDI is more profitable than hand watering for non-cole crops.

Another observation is the importance of techniques such as water harvesting occurring in conjunction with LCDI to reduce labour costs and provide a water source close to the field. This has been recognized by IDE and ICIMOD, both of which are embarking on linking LCDI and water harvesting strategies.

16. WATER USE EFFICIENCY

Irrigation systems may be evaluated on physical, biological, and economic aspects, and thus a single definition to compare irrigation efficiency for all irrigation systems is inappropriate. The term used to assess irrigation efficiency will depend on the analysis desired and the scale examined. Caution is needed in comparing results between studies not only due to the different terms to describe "efficiency", but also due to the different definitions for the same term.

One of the more common assessments of irrigation efficiency is water use efficiency (WUE) for which a range of definitions is used (Figure 16.1). As a result, care must be taken to determine whether WUE refers to the classic definition of 'water use efficiency' (the ratio of crop yield (biological or economic) to crop water use (transpiration (T) or evapotranspiration (ET)) (Viets 1962) or whether *de facto* it is referring to the 'efficient use of water'. Efficient use of water can result in water savings through various management practices (e.g. decreasing surface runoff) thereby allowing more hectares of crops to be grown, however it does not change the crop water use (either ET or T) factor found in Viets' (1962) definition of WUE.



DM = above-ground dry matter, Mg/ha IR = seasonal irrigation, mm

ET = evapotranspiration, mm T = transpiration, mm

EY = economic yield, Mg/ha

Vd = diverted water from a stream that was stored in the crop root zone

Vg = gross stream water diversion

[1] Viets 1962, [2] Stewart and Hagan 1973, [3] Bos and Nugteren 1978

Figure 16.1. Variations in WUE definitions

Each of the definitions presented in Figure 16.1 has limitations to its use within the literature. The Engineering ratio (see Figure 16.1) does not consider whether irrigation is necessary or whether the water stored in the crop root zone is beneficially utilized. When WUE is defined by the Irrigation ratio, additional management information is required to enable cross-study comparisons as increases in WUE may be due to other factors unrelated to water amounts e.g. yield increases due to fertilizer use would increase the WUE. Both of the above definitions are more a measure of the efficient use of water although they are often described as measures of WUE. The use of Evapotranspiration ratios in providing a comparison of WUE for irrigation methods/ management is confounded by the difficulty in measuring differences in soil evaporation and measuring ET accurately. Similarly, Transpiration ratios are compromised by the limitation of measuring T accurately (Howell *et al.* 1990).

In calculating the WUE of the different irrigation lines, a modified version of the Irrigation ratio was used:

$$WUE = CY/IR$$

Equation 5. Water-use efficiency equation used.
where:
CY = total cauliflower yield per line (g) (fruit mass only)
IR = seasonal irrigation water (mL)

WUE efficiencies were calculated (Table 16.1) for each line, with a higher WUE value indicating a more efficient use of water. Deficit irrigated lines (D1, D2, HW 3, HW 4) had a higher WUE than lines receiving full irrigation (D3, D4, D5, D6, HW 1,HW 2) (Table 16.1). This is because the 50% reduction in water use under deficit irrigation only resulted in a yield reduction in total cauliflower of 10-30%. Under deficit irrigation, the WUE of LCDI was higher than the hand-watered and the Western drip irrigated lines. The latter two irrigation methods had comparable WUE under deficit irrigation. The high WUE of LCDI under deficit irrigation, combined with the long-term savings in labour suggests that a farmer operating under conditions of water scarcity and limited labour availability (as if often the case) would be served best by LCDI.

Under full irrigation, the hand-watered lines had the highest WUE, followed by LCDI, and then Western drip irrigation. This is in part due to the experimental design, which stipulated that all plants were irrigated until they were either harvested or until the 90-day duration of the experiment expired. For hand-watered plants it is simple to discontinue irrigation of harvested plants. However, under drip irrigation, the entire line was irrigated until all plants had been harvested, regardless of how many plants were actually remaining. Thus, the total amount of water applied to the drip irrigated lines is inflated compared to an actual field situation, where irrigation would be stopped once harvesting began.

Table 16.1. Water use efficiency for each irrigation line

Irrigation method	Line # (Water amount)	Total water applied (mL)	Total cauliflower yield (g)	WUE (g/mL)
LCDI	D1 (Deficit)	622880	32159	0.052
Western	D2 (Deficit)	624640	24737	0.040
LCDI	D3 (Full)[1]	1182200	29751	0.025
Western	D4 (Full)	1179120	27385	0.023
LCDI	D5 (Full)	1144040	35083	0.031
Western	D6 (Full)	1138320	24202	0.021
HW	HW 1 (Full)	1032955	41097	0.040
HW	HW 2 (Full)	1123330	35122	0.031
HW	HW 3 (Deficit)	682833	27842	0.041
HW	HW 4 (Deficit)	686761	28632	0.042

[1]Full indicates that plants were receiving the full estimated daily water requirement.

This experiment indicates that farmers can successfully grow an additional crop on a field size of $180m^2$ with ~11,000 L of water. If the entire area is deficit irrigated this can be reduced to ~ 6000 L of water. Under deficit irrigation, 1 kg of cauliflower is produced per 23 L of water applied, while under full irrigation 1 kg of cauliflower is produced per 35 L of water applied. In comparison, approximately 1000 L of water is required to produce 1 kg of grain (Postel 1999). Thus, the overall efficiency of water use within this experiment is quite high, particularly under deficit irrigation. This is extremely important to farmers in water scarce areas, who although they may have a decline in the total yield, will still be able to produce a viable result.

A typical yield in 1998 for the lower Fraser Valley calculated for a comparable area is 260 kg. The total yield for the experiment was 306 kg. This value includes non-marketable cauliflower heads, however it does not include the mass of the inner leaves, which would be included if the cauliflower was sold commercially. Thus, the total yields produced within this experiment are comparable to commercial yields produced in California and British Columbia where cauliflower are typically furrow irrigated and sprinkler irrigated respectively (Koike *et al.*1997, BC Ministry of Agriculture 1998).

17. IRRIGATION CONCLUSIONS AND RECOMMENDATIONS

Under the field set-up of this study low cost drip irrigation (LCDI) had a better emission uniformity than Western-drip lines. The emission uniformity of LCDI may be classified as "fair". The simple baffle design of LCDI does result in a higher flow rate than the Western drip emitters, however flow rates (~3.3 L/hr) are still within values typical for drip irrigation. The higher flow rate means that less time is required to deliver a specified amount of water, which may be advantageous to the farmers. No difference to plant performance is expected due to the differences in flow rate. The flow rate of LCDI lines was sensitive to the water head for lines within ~ 3 m from the water source. Further studies are required to confirm this, as this will impact the amount of time a line should be irrigated. Farmers currently using LCDI use a set time to determine how much water to deliver.

Within any given irrigation regime, Western drip irrigation had a lower production of total cauliflower mass and aboveground biomass. This highlights the importance of appropriate technology. Although Western drip irrigation systems could be imported to places, the conditions under which it would be operated would likely result in suboptimal performance of the system, with subsequent reductions and high variability in crop yield. The LCDI alternative may perform better in a similar situation, and furthermore it is less expensive and easier to install and maintain.

Differences between LCDI and hand-watered irrigation depend upon the irrigation regime; under deficit irrigation LCDI had significantly greater cauliflower yield than hand-watered irrigation, under the morning-evening regime the inverse was true, and under the evening-only regime there was no significant difference in the cauliflower yield between the two irrigation methods. Without additional replications, conclusions about which irrigation method performed best overall, in terms of cauliflower production, would be misleading.

Differences in the SVWC between irrigation methods were not consistent between the three irrigation regimes. The SVWC likely did not influence plant performance in either the deficit irrigation or the evening-only irrigation regime. In the EO irrigation regime although significant differences in the SVWC existed at both the PM and the post PM measurement intervals the scale of the difference was small (1.0 %) and is likely inconsequential to plant performance. In the evening-only irrigation regime, no significant difference in SVWC occurred between the three irrigation methods. The results from the morning-evening irrigation line were dissimilar to the other two irrigation regimes. Significant differences between the lines occurred at all measurement times and were considerable. These differences appear to have had some influence on plant productivity. The SVWC content of the hand-watered irrigation method was significantly less than both of the drip methods, however, plant productivity was significantly higher. As the drip irrigated lines were at or above field capacity for the AM and post-PM irrigation, it is plausible that the frequent water applications in this regime may have caused water stress, due to reduced soil aeration, and subsequent declines in plant productivity. Variability in the cauliflower plants may also have influenced the results. Soil quality within the field was not significantly different between locations and thus, although within-field soil variability may have been a contributing factor it is not expected to be to have been of considerable importance.

The SVWC of the deficit lines was significantly less than that measured in five of the six irrigation lines receiving full irrigation and deficit irrigated lines had lower cumulative cauliflower yields, crop residue, and biomass production than irrigated lines receiving the full daily water requirement needs. However, the water use efficiency of deficit irrigated lines was greater than lines receiving 100 % of the daily water requirements due to a 50% saving in water without a comparable drop in crop yield. Overall, the water use efficiency of the experiment was high with the production of 1 kg of cauliflower requiring 23-35 L of water. In contrast, to produce 1 kg of grain, 1000 L of water is required. In addition, cauliflower yields were comparable to those of California and the Lower Fraser Valley in British Columbia.

Differences in economics and labour, both of which are important variables to farmers, exist between hand watering and LCDI. After the cultivation of one crop, hand watering will generate a greater profit. However, after the capital costs of the LCDI system have been paid for (within 2 crops depending upon the sale price) LCDI will generate a greater profit due to lower labour requirements. Under LCDI, farmers are spared the tedious nature of watering each individual plant. In addition, expanding the irrigated area results in disproportionately higher labour costs for hand-watering than for drip irrigation. Furthermore, under water scarce conditions where deficit irrigation is most likely to be employed, cauliflower mass was significantly greater for LCDI than for hand-watered irrigation. Therefore, in the long-term, LCDI is likely a better overall irrigation strategy. Further trials with cauliflower and other crops, which may be more sensitive to watering methods, would confirm these preliminary results.

17.1. Recommendations and Improvements

Experimental designs are typically constrained by human and financial resources as well as by logistical factors. Modifications and improvements of the experimental design for future studies under ideal conditions include:

1) the measurement of matric potential rather than the soil volumetric water content at varying depths. This would allow plant water stress to be measured directly rather than indirectly through soil volumetric water content. It would also enable irrigation to be based directly on plant need and provide an empirically based ideal irrigation volume.

2) access to an evaporation pan to measure potential evapotranspiration.
3) evaluate the evaporative losses of the system components. This would allow potential differences in soil evaporation between the different irrigation methods to be assessed.
4) an increased number of replicates with trials held in the pre-monsoon and winter seasons over a number of years for a variety of crops. In addition, a randomized design and monitoring of water flow through a flow meter. These latter factors were not possible under the operating conditions of the experiment.
5) similar experiments on different soil types.
6) screening of seedlings to maintain a consistent quality. Although cauliflower seedlings used were of similar quality between the rows, they were not screened specifically for quality prior to planting. In future studies, it is recommended that seedlings be screened, thus eliminating a potential source of variation that may influence the results independent of the irrigation method.
7) introduce greater variation in irrigation scheduling (e.g. compare the effect of irrigating every day, every 3 days and every 4 days on crop yield and plant stress).
8) improved on-farm trials. On-farm trials allow technology to be tested and verified in a local setting. This form of on-farm research typically involves a contractual relationship between the farmers and researchers, where a farmer's land and/or services are hired or borrowed (for a complete discussion of on-farm research methodology see Biggs 1989). The criteria used to select farmers should be based on the specific research objectives and the purpose for farmer participation. If the goal is simply to test and verify the technology then a farmer who can guarantee the conditions of the contract should be selected (Biggs 1989). Farmer selection is critical in on-farm research and an understanding of community dynamics, gained either through local contacts, field staff, or time spent in the community, is essential to ensuring successful field trials. On-farm trials are valuable, however they require considerable logistical co-ordination.

18. SUMMARY & LINKAGES

18.1. Summary: Soil Fertility

An examination of input types and amounts, nutrient budgets, and the soil status of non-red soils in intensively managed and less-intensively managed sites within the Jhikhu Khola watershed provided an understanding of the effects of agricultural intensification on soil fertility dynamics.

Agricultural intensification within the Jhikhu Khola watershed has been characterized by a shift to a triple cropping rotation that incorporates cash crops, predominantly potato and tomato. Cropping rotations under intensive agriculture have higher soil nutrient uptake than cropping rotations under less-intensive agriculture. Farmers have responded to this greater plant nutrient uptake by significantly increasing the amount of compost and chemical fertilizers applied, particularly diammonium phosphate, which contains 26% more phosphorus (P) per unit mass than previous fertilizers used. This has resulted in positive nutrient budget for P and high levels of available soil P in both intensively managed khet and bari sites. This result was unexpected as previous studies determined that available P was a limiting nutrient within the watershed.

In contrast, levels of exchangeable potassium (K) in the soils of khet sites have been negatively affected by the intensification. The introduction of a triple crop rotation that incorporates potatoes, but has inadequate K inputs has resulted in deficit K budgets and significant declines exchangeable K in intensively managed khet sites. Previously, potassium has not been a concern as a result of the micaceous parent material within the watershed.

Agricultural intensification has significantly altered the soil fertility dynamics of phosphorus and potassium in opposite ways. To prevent further imbalances in soil fertility, nutrient management should focus on the entire system, rather than on an individual nutrient basis.

18.2. Low-cost drip irrigation

A comparison between low-cost drip irrigation (LCDI), Western drip irrigation, and hand-watering on the soil volumetric water content and the cauliflower productivity of each method did not result in any one irrigation method performing better for all irrigation regimes tested. However, it was demonstrated that Western drip irrigation had a lower performance under the experimental field conditions. Intuitively, it was expected that LCDI would perform better than hand-watering, however this appeared to be the case only under deficit irrigation. Both hand-watering and LCDI resulted in good cauliflower yields, however LCDI is a better long term irrigation strategy as labour costs are less, water application is easier, and it appears to perform better under deficit irrigation.

Irrigation methodology and theory has primarily been developed for temperate climates. The application of such theories e.g. the determination of permanent wilting point, to determine water requirements and experimental design should be used with caution in a subtropical setting. Farmers will tend to use LCDI for a variety of crops. Thus, incorporating a variety of crops as indictors may provide an improved overall comparison of the different irrigation methods.

18.3. Linkages

Agriculture is the dominant activity of Nepal, a country that faces ever-increasing pressures on its natural resource systems to meet the food demands of a rapidly growing population. Two important elements towards attaining food security are irrigation and the maintenance of soil fertility.

The expansion of irrigation is considered key to increasing agricultural production, typically this is associated with a move towards more efficient management of existing irrigation systems or more commonly, the development of new irrigation projects involving surface water storage, spillways, canals, and drainage systems. This solution is of little benefit to the Middle-Mountain area, where topographical factors limit the suitability of such strategies. Furthermore, the expansion of canal-style irrigation projects will not address the water shortages faced on bari lands whose productivity is limited by water scarcity during the winter and pre-monsoon seasons. During these seasons, farmers may have access to water from springs, or from baseflow of small streams, however, quantities are insufficient to irrigate crops by furrow or border irrigation, which require substantial volumes of water over a short period of time. The introduction of low-cost drip irrigation (LCDI) offers the potential to substantially increase the area under irrigation within bari lands, enabling farmers to cultivate an additional crop without the labour costs and diligence of watering by hand. LCDI provides farmers with the opportunity to improve their food security, their nutritional intake, to generate a cash income, and most importantly to increase the productivity of small-scale dry-land farming systems.

Although the use of LCDI on bari fields will result in an increase in the number of crops grown on a piece of land, thus intensifying the production process, it does not necessarily imply that LCDI will have a negative impact on soil fertility, in fact it may promote the maintenance of soil fertility. The maintenance of soil fertility is not only related to input amounts, but also to social and economic factors. Soil fertility maintenance is often not a priority for farmers whose land does not meet their household's basic needs. Thus, the generation of an additional food and income source through LCDI, may actually result in the promotion of soil fertility. Nutrient budget modelling showed improvements in the soil fertility of bari sites under intensive agriculture. Similarly, intensification as a result of LCDI may contribute to positive changes in nutrient management. In addition, although LCDI will intensify agriculture on bari lands, it may reduce agricultural expansion into marginal and forested areas. Low levels of soil fertility already characterize these areas and their conversion into cropland does not significantly benefit overall system productivity.

Other potential benefits LCDI may offer to soil fertility is its ability to cultivate a crop on bari fields during the pre-monsoon season. This will provide some degree of vegetative cover, thereby reducing soil erosion and subsequent nutrient losses. Furthermore, LCDI may increase farmer awareness of the importance of balanced nutrient additions as they see visual signs of soil micronutrient deficiencies on the vegetable crops they are cultivating. In addition, the introduction of LCDI can act as a platform for extension activities dealing with soil fertility and nutrient management.

The long term-effects of LCDI on soil fertility are difficult to predict as human behavioural adaptations are involved. If farmers simply use LCDI to cultivate an additional crop without considering the need for appropriate amounts and types of inputs, then declines in soil organic matter content and increased soil acidity may result. Alternatively, LCDI may promote soil fertility, through better management of nutrient cycles, increased investment in land management, the maintenance of a vegetative cover during the pre-monsoon season, and reduced pressures to expand into marginal areas. The linkages between irrigation and soil fertility indicate that both issues need to be addressed in an integrated approach. Long-term monitoring of soil fertility in plots using LCDI will further elucidate these linkages.

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APPENDICES

Appendix 1: Crop Survery Jhikhu Khola Watershed: PARDYP Program

Farmers Name: Date:
Household # Aerial photo #:
Ward: VDC:

A. List the dominant crop rotation typically planted in the last 5 years.
1.
2.
3.
4.
5.

CROP YIELD AND INPUT DATA FOR THE MOST RECENT YEAR

Crop Type	Yield/ Ropani	Compost Amount / Ropani	Chemical Fertilizer		Pesticide		
			Type	Amount (kg/Rop)	Type	Amount Packets/ropani	Application Frequency
Rice							
Potato							
Tomato							
Maize							
Wheat							
Other crop type (s):							

B. Have you noticed any changes in your soil quality in the past 5 years? Yes ☐ No ☐

If yes, describe:

C. During the past 5 years have you noticed an:
Increase ☐ Decrease ☐ No change ☐ in your crop yield?

D. Has your crop yield increased due to more chemical fertilizer inputs? ☐ Yes ☐ No

If yes, by how much (%)

E. Has your crop yield increased due to more compost additions? ☐ Yes No ☐

If yes, by how much (%)

F. List any reasons you may have for a lack of increase in crop yield:

CROP YIELD AND INPUT DATA 5 YEARS AGO

Crop Type	Yield/ Ropani	Compost Amount / Ropani	Chemical Fertilizer		Pesticide		
			Type	Amount (kg/Rop)	Type	Amount Packets/ropani	Application Frequency
Rice							
Potato							
Tomato							
Maize							
Wheat							
Other crop type (s):							

Appendix 2. Hydrosense Specifications

Resolution	± 0.1 %
Accuracy	: ± 3.0 % volumetric water content with a electrical conductivity < 2 dS/m
Range	0 % to saturation
Response time	< 50 milliseconds
Total soil volume measured	12 cm probe = 650 cm^2 20 cm probe = 1100 cm^2

Appendix 3. Nutrient uptake by rice

Yield (kg/ha)	Component	Nitrogen (N)		Phosphorus (P)		Potassium (K)		Reference
		kg/ha	%	kg/ha	%	kg/ha	%	
2500	grain							Carson 1992
	whole plant	30	0.5	7	0.13	37		
1323	grain							Suwal *et al.* 1991
	whole plant	54	1.8	3	0.09	61		
1500	grain							LRMP 1986
	whole plant	42	1.2	8	0.22	24		
5040	rough rice	67		12		11		U.S. Borax 1979
6720	straw	40		6		75		
	whole plant	107	0.9	17	0.13	86	0.75	
3360	grain							Landon 1984
	whole plant	54	0.7	26	0.35	38	0.50	
1500	grain	35		7		10		Sanchez 1976
1500	straw	7		1		18		
3000	whole plant	42	1.4	8	0.26	28	0.91	
7900	grain	85						Olson and Kurtz 1982
10000	straw	40						
	whole plant	125	0.7					
9800	rough rice		1.5		0.26		0.25	DeDatta and Mikkelsen 1985
8300	straw		0.9		0.04		2.32	
	whole plant		1.2		0.18		1.16	
2430	rough rice	23		5		10		Grist 1986
4930	straw	22		5		43		
	whole plant	45	0.6	10	0.13	53	0.66	
4030	rough rice	56		10		9		Foth 1990
5600	straw	34		6		65		
	whole plant	90	0.9	16	0.17	74	0.75	
Average	**whole plant**		**1.0**		**0.17**		**0.83**	

Appendix 4. Nutrient uptake by maize

Yield (kg/ha)	Component	Nitrogen (N)		Phosphorus (P)		Potassium (K)		Reference
		kg/ha	%	k/ha	%	kg/ha	%	
1600	grain							Carson 1992
	whole plant	75	2.1	11	0.31	50		
1560	grain							Suwal *et al.* 1991
	whole plant	53	1.5	10	0.31	12		
6270	cob							Landon 1984
	whole plant	165	1.2	24	0.17	135		
11760	cob	151		26		44		U.S. Borax 1979
10080	stover	113		17		161		
	whole plant	264	1.2	44	0.22	205	0.75	
1000	grain	25		6		18		Sanchez 1976
1500	stover	15		3		22		
2500	whole plant	40	1.6	9	0.35	40	1.33	
6272	grain	109		21				Canadian Fertilizer Institute 1998
	stover	63		9				
	whole plant	171	1.2	31	0.22	31		
5000	cob			15				Hanway and Olson1980
	stover			6				
	whole plant			21	0.17			
10000	grain							Olson 1978
	dry matter	170	0.8	33	0.13	210	0.75	
	grain	129		31		47		Olson and Sander 1988
	stover	62		8		188		
9450	dry matter	191	2.0	39	0.39	205	2.08	
9400	grain	151		26				Foth 1990
10080	stover	112		18				
	whole plant	263	1.4	44	0.22			
9000	dry matter	115	1.3					Russelle *et al.* 1983
8400	grain							M iller and Donahue 1990
	whole plant	246	1.3	39	0.22	218	0.91	
Average	**whole plant**		**1.4**		**0.26**		**1.16**	

Appendix 5. Nutrient uptake by wheat

Yield (kg/ha)	Component	Nitrogen (N)		Phosphorus (P)		Potassium (K)		Reference
		kg/ha	%	k/ha	%	kg/ha	%	
1415	grain							Carson 1992
	whole plant	30	1.0	7	0.22	25	0.83	
2310	grain							Suwal *et al.* 1991
	whole plant	54	1.1	10	0.17	27	0.50	
4804	whole plant	64	1.3	5	0.09	23	0.50	Sherchan *et al.* 1991
1675	grain							Sherchan *et al.* 1995
	whole plant	45		4		17	0.42	
1675	grain							Landon 1984
	whole plant	54	1.5	11	0.31	11	0.25	
600	grain	12		2		2		Sanchez 1976
1000	straw	3		1		14		
1600	whole plant	15	0.8	3	0.17	17	1.00	
3360	grain	58		13				Canadian Fertilizer Association 1998
	straw	17		3				
	whole plant	15	1.0	15	0.22	16		
5000	grain							Olson 1978
	whole plant	110	1.0	22	0.22	58	0.50	
7300	grain							Halvorson *et al.* 1987
	whole plant	176	1.1	21	0.13	110	1.49	
4030	grain							Miller and Donahue 1990
	whole plant	140	1.6	24	0.26	102	1.16	
3600	grain	84		19		22		U.S. Borax 1979
4500	straw	34		4		49		
	whole plant	118	1.5	23	0.26	71	0.83	
	grain	56		12		14		Foth 1990
2690	straw	22		3		32		
3360	whole plant	78	1.3	16	0.26	46	0.75	
Average	**whole plant**		**1.2**		**0.22**		**0.75**	

Appendix 6. Nutrient uptake by potato

Yield (kg/ha)	Component	Nitrogen (N)		Phosphorus (P)		Potassium (K)		Reference
		kg/ha	%	k/ha	%	kg/ha	%	
20000	whole plant	140	0.70	17	0.09	158	0.79	FAO 2000b
40000	whole plant	175	0.44	35	0.09	257	0.64	FAO 2000b
62000	whole plant	147	0.24	19	0.03	403	0.65	Sanchez 1976
1000	whole plant	4.5	0.45	0.6	0.06	7.1	0.71	Dean 1994
1000	whole plant	5.9	0.59	1.1	0.11	10.7	1.07	Dean 1994
Average	**whole plant**		**0.48**		**0.07**		**0.77**	
50000	tuber	180	0.36	25	0.05	200	0.40	Cooke 1982
30000	tuber	80	0.27	50	0.17	125	0.42	Landon 1984
30000	tuber	120	0.40	80	0.27	160	0.53	Landon 1984
40000	tuber	120	0.30	24	0.06	183	0.46	Ahmad 1977
1000	tuber	2.6	0.26	0.7	0.07	4.7	0.47	Dean 1994
1000	tuber	4.2	0.42	0.5	0.05	4.8	0.48	Dean 1994
1000	tuber	4.2	0.42	0.9	0.09	5.2	0.52	Dean 1994
1000	tuber	3.2	0.32	0.7	0.07	4.3	0.43	Dean 1994
44000	tuber	77	0.18	14	0.03	224	0.51	Sanchez 1976
1000	tuber	3.9	0.39	1.4	0.06	4.9	0.41	Velayutham and Reddy 1987
Average	**Tuber**		**0.33**		**0.09**		**0.46**	

Appendix 7. Nutrient uptake by tomato.

Yield (kg/ha)	Component	Nitrogen (N)		Phosphorus (P)		Potassium (K)		Reference
		kg/ha	%	k/ha	%	kg/ha	%	
5000	fruit	15	0.30	2	0.04	20	0.40	von Uexkull 1978
10000	fruit	29	0.29	4	0.04	40	0.4	
25000	fruit	73	0.29	10	0.04	100	0.4	
27800	fruit	54	0.19	7	0.02	69	0.25	Splittstoesser 1990
30000	fruit	100	0.33	28	0.09	133	0.44	Landon 1984
30000	fruit	150	0.50	48	0.16	199	0.66	Landon 1984
1000	fruit	3	0.30	0.3	0.03	3.5	0.35	Hedge and Srinivas 1990
38000	fruit	113	0.27	9.5	0.03	116	0.31	Yawalkar *et al.* 1961
40000	fruit	110	0.28	13	0.03	125	0.31	FAO 2000b
	fruit		0.33		0.00		0.42	Potash and Phosphate Institue 2000
Average	**fruit**		**0.31**		**0.05**		**0.39**	

Appendix 8. Nutrient uptake by soyabean

Yield (kg/ha)	Component	Nitrogen (N)		Phosphorus (P)		Potassium (K)		Reference
		kg/ha	%	k/ha	%	kg/ha	%	
3363	grain	73	2.17		0.24	26.3	0.78	Tisdale and Nelson 1966
1000	grain	66.8	6.68		0.77	44.4	3.68	Velayutham and Reddy 1987
800	grain	20	2.50	30	3.75	60	7.50	Landon 1984
1300	grain	20	1.54	30	2.31	60	4.62	Landon 1984
2400	whole plant	224	9.33	19	0.79	81	3.38	FAO 2000b
1000	whole plant	50	5.00	4	0.40	15.3	1.53	Potash and Phosphate Institue 2000
1000	whole plant	76	7.60	5.6	0.56	33	3.30	Canadian Fertilizer Institute 1998
Average	**whole plant**		**7.31**		**0.58**		**2.74**	

Appendix 9. Nutrient uptake by onion

Yield (kg/ha)	Component	Nitrogen (N)		Phosphorus (P)		Potassium (K)		Reference
		kg/ha	%	k/ha	%	kg/ha	%	
16800	Bulb	50	0.30	10	0.06	37	0.22	Foth 1990
35000	Bulb	60	0.17	10	0.03	37	0.11	Landon 1984
45000	Bulb	100	0.22	20	0.04	66	0.15	Landon 1984
35000	whole plant	120	0.34	50	0.14	160	0.46	FAO 2000b
44800	whole plant	135	0.30	11	0.02	87	0.19	Canadian Fertilizer Institute 1998
44800	whole plant	163	0.36	24	0.05	129	0.29	Canadian Fertilizer Institute 1998
Average	**whole plant**		**0.34**		**0.07**		**0.31**	

Appendix 10. Labour costs associated with cauliflower production by three different irrigation methods.

	Low Cost Drip Irrigation		Western drip		Hand-watered	
Labour Activity	Total time (days)	Cost (NRp)	Total time (days)	Cost (NRp)	Total time (days)	Cost (NRp)
Land preparation, system set-up, weeding	1	75	1	75	1	75
Application of pesticides	0.5	38	0.5	38	0.5	38
Fetching water [a]	13	975	13	975	13	975
Shifting irrigation lines[b]	1.5	113	0	0	0	0
Irrigation	0	0	0	0	6	450
Total	**16**	**1200**	**14.5**	**1088**	**20.5**	**1538**

[a] Based on a 22 minute return trip to fetch 25 L of water (Merz *et al.* 1999).
[b] It is assumed that it requires 20 minutes to shift 8 lines.