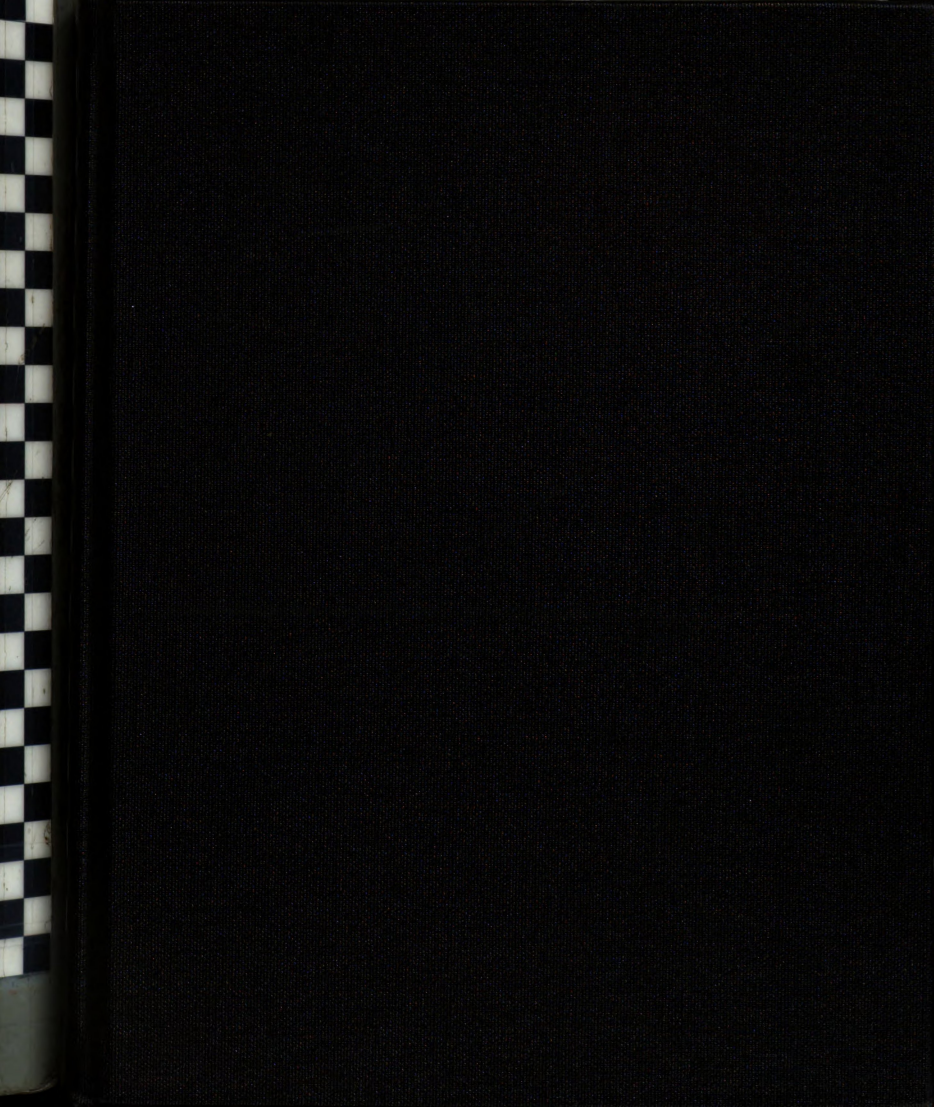




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A SYSTEM

**A SYSTEMS ASSESSMENT OF PHOSPHOROUS FERTILIZER FOR USE IN
Phaseolus vulgaris L. PRODUCTION IN TANZANIA.**

By

Cornel Lawrence Rweyemamu

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Crop and Soil Sciences

1995

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ABSTRACT

A SYSTEMS ASSESSMENT OF PHOSPHOROUS FERTILIZER FOR USE IN *Phaseolus vulgaris* L. PRODUCTION IN TANZANIA

By

Cornel Lawrence Rweyemamu

Phosphorous (P) is critical to improving fertility for sustainable agriculture in Tanzania. A field study was conducted during the 1993 and 1994 growing seasons at the Sokoine University of Agriculture farm (6° 50'S, 37° 39'E at 525 m altitude) in the Morogoro region of Tanzania. The objective of the study was to evaluate the P version of the BEANGRO model under Tanzanian conditions for sensitivity to P response by a bean crop grown with different sources and levels of P fertilizers under rainfed and irrigated conditions. The study also assessed the growth and yield of a bean crop as influenced by Minjingu phosphate rock (MPR) used as a directly applied phosphate rock (DAPR) fertilizer in comparison with triple superphosphate (TSP) fertilizer; and the residual effectiveness of MPR in comparison with TSP fertilizer on bean crop performance. Cultivar Canadian Wonder was planted at 25 plants m⁻² in a complete randomized block design with three replications in each block. The MPR soft ore (30% P₂O₅) and TSP (46% P₂O₅) fertilizers were broadcast and incorporated in each plot at planting. The seven treatments used in the study were: 0 kg P ha⁻¹; 22 kg P ha⁻¹-TSP; 22 kg P ha⁻¹-MPR; 44 kg P ha⁻¹; 88 kg P ha⁻¹-TSP; 88 kg P ha⁻¹-MPR; and 176 kg P ha⁻¹-MPR. The irrigated experiment was sown on a soil with a pH of 5.43; the rainfed experiment was sown on a soil with a pH of 4.50. Model validation was made by comparing predicted with field measured data. Despite incidence of diseases and pests during

the study, the model accurately predicted the growth cycle, yield and P uptake under irrigated conditions. The model proved to be sensitive to soil initial P and model functions related to uptake. Laboratory analysis with neutral ammonium citrate (NAC) indicated MPR was a highly reactive rock with the value of 6.7% P_2O_5 . The study also showed that MPR performed well under irrigated conditions, and that the residual effect of TSP was higher than that of MPR fertilizer one year after application under rainfed conditions.

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DEDICATION

I affectionately dedicate this work to my mother, Regina, for her strong support and her prayers, my daughter, Evangelyn, for her tolerance, my brothers, sisters, and friends who encouraged me to seek out more knowledge in life.

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I also express my recognition to Dr. S. H. Chien, senior soil chemist at the International Fertilizer Development Center (IFDC) in Muscle Shoals, Alabama for genuine interest in my work, determination of Minjingu phosphate rock (MPR) characteristics, and his suggestions during the preparation of this manuscript. I am further thankful to Dr. Walter

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T. Bowen, systems scientist (IFDC), and Mr. Brian Baer, program analyst for the Homer Nowlin Chair, at MSU for working tirelessly on the phosphorous sub-model, and for their computer assistance.

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CHAPTER 1

INTRODUCTION

Phaseolus vulgaris L. (Fabaceae) a C₃ plant is the most widely grown of the four cultivated species of *Phaseolus*. The other three species are *Phaseolus coccineus* L. (scarlet runner bean), *Phaseolus lunatus* L. (lima bean), and *Phaseolus acutifolius* A. Gray (teparty bean). The *P. vulgaris* L. crop is known by various names such as kidney beans, haricot beans, snap beans, dry beans, common beans, etc. In Eastern Africa in general, and Tanzania in particular, they are usually referred to simply as beans in English and "maharagwe" in Kiswahili. In this study the name "beans" will be used. Beans are believed to have originated in Central, and South America in Andean zones. In the 16th century the Spaniards and Portuguese took beans to Europe, and from there to Africa and various parts of the world (Pulseglove, 1968; Gentry, 1969). In the 1930s, new varieties were introduced in Tanzania mainly for canning purpose (Macartney, 1966).

Beans are a major staple food worldwide, and different growth habits have been developed to meet different yield, and yield stability requirements (Silbernagel and Hannan, 1988). Bean cultivars are classified according to growth habit and period of growth (Voysest and Dessert, 1991). CIAT (Centro de Internacional de Agricultura Tropical) classifies beans into determinate, and indeterminate genotypes. The determinate genotypes, have a main stem

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¹Uno, N.A., 1984.
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and the lateral branches terminate in an inflorescence, while the indeterminate genotypes have main stem and the lateral branches are topped by vegetative meristem capable of continuous organogenesis (Debouck, 1991). These growth differences are genetically controlled (Bliss, 1971). Further, bean varieties are referred to as "early" or "late" in reference to the environment where they are grown (Voyses and Dessert, 1991).

Beans are the most important grain legume crop grown in Tanzania. They are mainly grown for their dry seed, but are also grown for fresh pod, and leaf consumption. They form an important component of the diets of many people in Tanzania. Referred to as "food for the poor", beans are a particularly important source of protein for families with low income and limited access to animal protein in rural areas. About 30% of produced grain is marketed for urban populations where animal protein is becoming less affordable, while the remaining is consumed at farm level. Although cultivars developed for monoculture cropping systems are small-seeded, consumers prefer large seeded beans (i.e., $>400 \text{ mg seed}^{-1}$). Also, most farmers prefer bean straw to maize stover in feeding their dairy cattle because of bean straw's high quality and proportion of edible stem portions (Urio and Mlay, unpublished report 1984¹).

Beans are grown during the short and the long rainy seasons in those parts of Tanzania where there is bimodal rainfall. However, they are commonly cultivated during the long rainy season in most bean producing areas (Karel *et al.*, 1981). Agronomic practices used in bean production differ from one area to another depending on factors such as

¹Urio, N.A., and G.I. Mlay. 1984. First progress report on diagnostic survey among smallholder dairy farmers in Hai District-Tanzania, IDRC Project File No. 3-P-82-0035.

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temporal and spatial arrangements on the basis of physical, biological, and social economic constraints. One such practice, slash and burn, is usually used by farmers to clear the land after a fallow period. Depending on whether zero or minimum tillage is used farmers begin land preparation at the onset of the rainy season using hand-hoes, and animal traction devices such as moldboard plows and tractors for those farmers who can afford the equipment.

For bean crops grown on traditional farms, there are no specific planting arrangements such as plant spacing changes with cropping system, rainfall, soil type, crop compactions, and length of the cropping season. Ridges are commonly built in contours across slopes, especially along the Uluguru mountains in the Morogoro region, to reduce erosion. In monocultural systems, planting methods usually follow conventional techniques used in high-input systems. In intercrops or multiple cropping systems, one or two bean seeds are planted in holes about 2.5 cm in diameter and 5.0 cm deep in the soil. High rainfall variability and low soil water retention capacity are mainly responsible for poor bean crop establishment.

Few farmers apply irrigation. This is because irrigation water is not always available, and irrigation facilities are not within economic reach of most farmers. However, when furrow irrigation is applied, the beans are usually grown on ridges. If the crop is not irrigated or planted at the right time, it is mostly affected by water stress from flowering to early pod set, and yield components are more likely to be affected by water stress (Stoker, 1974). Overall response of beans to water stress depends on the cropping system. In Eastern Africa, there can be severe yield reduction in a bean crop grown in bean-maize intercrops because of the strong competition of maize for water and nutrients (Fisher, 1977). However, an important intercropping system found in Kagera region where beans are grown in association with

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Beans are generally grown in environments with air temperatures ranging from 16° to 26°C. The length of the growing season depends mainly upon the variety used and temperature which in turn is affected by altitude. In the northern and southern highlands of Tanzania, beans take about three months to mature, while in the lowlands, they take about two months to reach maturity. Improved varieties are grown on a small scale by only a few farmers in Tanzania. Most farmers grow "mixed beans" or "local varieties" which have a great diversity of growth habit, vegetative characters; seed color, size and shape. Most varieties grown by the farmers are low yielders. Determinate, indeterminate non-climbing and climbing beans are grown. The exact number of the varieties grown in the country is not known because often a variety is referred to by different names in different parts of the country (Karel *et al.*, 1981). There are a number of commercially available varieties which include Canadian Wonder, Selian Wonder, Lyamungo 85, Uyole 84; and Kabanima supplied by Tanzania Seed company (TANSEED).

Bean production statistics published annually by Food and Agriculture Organization (FAO) vary in reliability from reasonably accurate estimates to imprecise approximations (Adams, 1984). For example, bean production for 1992/93 from the Ministry of Agriculture (MOA) was estimated at 233,500 metric tons from 179,600 ha, i.e., 1,300 kg ha⁻¹ (MOA, 1993) (these estimates are on the high side). Similar estimates were given for previous years (Table 1.1). Farmers' yields usually average 600 kg ha⁻¹ (Silbernagel and Teri, 1990). However, improved varieties used in research trials have given yields of more than 1000 kg

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^a Source: Ministry of Agriculture

^b Area is in '000 ha

^c Production is in '000 t

^d Yield (seed) is in kg/ha

Karel et al.

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ha⁻¹ (Karel *et al.*, 1981; Silbernagel and Teri, 1990). In the Arusha region, about 25,000 ha of beans are grown on a large scale on contract to foreign seed firms. The cultivars grown are determinate bushy types selected for their acceptability in Europe as snap beans, and are produced in monoculture. Since the commercial farms receive more inputs, including aerial application of pesticides, their yields can be as high as 1600 kg ha⁻¹. In general terms, bean yields in Tanzania are higher (i.e., > 1000 kg seed ha⁻¹) in agricultural zones found in high altitudes (> 1000 m) than in areas with elevations below 1000 m.

Table 1.1 Average annual national bean production in Tanzania from 1988/89 to 1992/93⁺.

	<u>Year</u>				
	1988/89	1989/90	1990/91	1991/92	1992/93
Area ^a	198.54	180.65	232.00	197.68	179.60
Prod. ^b	337.31	319.18	290.80	256.99	233.50
Yield ^c	1699.00	1767.00	1253.00	1300.00	1300.00

⁺ Source: Ministry of Agriculture (MOA, 1993).

^aArea is in '000 hectares

^bProduction is in '000 metric tons

^cYield (seed) is in kg ha⁻¹

Karel *et al.* (1981) summarized some of the major insects that attack bean plants in Tanzania. Some of the most important insects include adult chrysomelid beetles (*Ootheca benningseni* Weise) which feed on bean seedlings, and plants, and can reduce bean yield by 18 to 31% (Karel and Rweyemamu, 1985) while bean aphids (*Aphis fabae* Scop.) can reduce

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yield by 37%. Yield decline, however, has been found to be less serious in multiple cropping systems than in monoculture systems partly because the diversity of crops grown does not provide a uniform background for pest manipulation. This has been shown on the incidence of the bean aphids in the bean-maize intercrop (Kennedy *et al.*, 1961; Ogenga-Latigo *et al.*, 1992). Few farmers use insecticides in Tanzania. They rely on the natural mortality factors to suppress insect populations.

Evidence shows that diseases account for more severe bean losses than insect damage in most parts of Tanzania. Diseases affect the bean crop in two ways: (I) by causing loss of yield and (ii) by reducing the quality of the seed (Karel *et al.*, 1981). More pathogens are associated with beans in

Africa, and Latin America than in temperate bean-growing regions of North America and Europe (Beebe and Pastor-Corrales, 1991). Halo blight (*Pseudomonas syringae* pv *phaseolicola* (Psp)); bean common mosaic (BCMV) a viral disease; rust (*Uromyces appendiculatus* var. *appendiculatus*), and angular leaf spot (*Phaeoisariopsis griseola*) are the most economically damaging bean diseases in Tanzania (Teri *et al.*, 1990). Intercropping bean with maize has been reported to reduce disease incidence and severity in the bean crop (Katunzi *et al.*, 1987). However, in a study that used the Canadian Wonder bean cultivar and maize intercrop, Mabagala and Saettler (1991) concluded that intercropping may increase seed infection with halo blight bacteria. Avoidance is currently a principal method for disease management by small bean producers. In Tanzanian situations where farmers rarely use purchased inputs in bean production, breeding for broad, multiple resistance is suggested as the best strategy of disease control (Teri *et al.*, 1990).

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Weed infestation is another major limiting factor in bean production for Tanzania. However it is usually less of a problem in intercropping than in monocropping systems. Chemical weed control is virtually nonexistent in intercrop, multiple and mixed cropping systems. In areas where monoculture is practiced, weed control is done manually two or three times during the early part of the growing season depending on the type of weed species in the area. Studies in Morogoro have shown that the severity of weed competition is between two to four weeks after planting which is regarded as the critical period for beans grown under monoculture conditions (Mbuya *et al.*, 1986). Manual weed control is a high labor requirement in small-scale bean production systems in Eastern Africa. Thus the use of large size, high leaf area index and high yielding bean cultivars is sometimes recommended as the means of suppressing weeds (Wortmann, 1993). In most cases, weeds are pulled or hoed and left on the ground to dry.

Soil fertility research in Tanzania was initially commodity oriented with emphasis on estate crops such as cotton, coffee, sisal, and tea. Since 1974 studies on other crops, including bean response to fertilizers, have been conducted. Currently, CIAT maintains a comprehensive program on bean research, and works cooperatively with the MOA under national programmes. A special initiative which was launched in 1980 entitled 'The USAID Title XII Bean/Cowpea Collaborative Research Support Program links American Universities with national research institutions in bean research. For example, Washington State University (Pullman) collaborates with Sokoine University of Agriculture (Morogoro), Tanzania in dealing with problems affecting production , and utilization of beans on subsistence farms.

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General benefits of fertilizer use in developing countries such as Tanzania have been identified by Baanante *et al.* (1989). Only one inoculant "nitrosua" has been developed for beans in Tanzania, and it is currently being tested under field conditions (Salema, 1987; Msumali, 1992). In most cases, the effects on nitrogen (N), phosphorous (P), and potassium (K) have been evaluated together in the same studies (Mkeni, 1989).

The application of P in beans results in increased plant growth (Yan *et al.*, 1995a), and seed yield (Manrique, 1986; Lynch *et al.*, 1991; Ya *et al.*, 1995b), N-fixation (Graham and Rosas, 1979), and radiation-use-efficiency (RUE) (Manrique, 1993). However, research findings on beans reported by Giller *et al.* (1988), and Semoka *et al.* (1990) on the use of Minjingu phosphate rock (MPR) as a direct applied P fertilizer have shown conflicting results. The Diagnosis and Recommendation Integrated System (DRSI) shows that the critical nutrient level (CNL) for the bean crop grown in East Africa is 0.32% P (Wortmann *et al.*, 1992).

Using the Bray-I method as recommended by Nandra (1974), the available P in the Morogoro region is categorized by Singh and Uriyo (1980) as 0-15, 15-25, 25-30, and > 30 ppm as low, medium, high and very high. Samki and Harrop (1984) reported the occurrence of acid soils in every district of Tanzania. The FAO-UNESCO (1974) soil map shows that Ultisols and Oxisols cover a large area of Tanzania. These soil orders are generally characterized by low available P, high fixing capacity, and low pH (Sanchez and Uehara, 1980). According to Sanchez and Uehara (1980), soils with high P fixing capacity are those which require addition of at least 200 kg P ha⁻¹ to provide an equilibrium soil solution concentration of 0.2 mg P kg⁻¹ of soil. However, current definition by CIAT shows that such

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soils should have the clay content of the top soil >35%, and free Fe oxide/clay ratio >1.5 (Mokwunye and Hammond, 1992).

The variation of soil types is very high in Tanzania. Uriyo and Singh (1978) have shown that where soils were young, the parent material rich in P-bearing minerals, Ca-P was the dominant inorganic-P fraction and where the soils were highly weathered, Al-P and Fe-P were the dominant fractions. In the western Arusha region (where commercial bean production is practiced), the bean crop thrives on the volcanic soils (Allen *et al.*, 1989). In most of the other areas such as Tanga, Kagera, and Morogoro where bean production is important, yields can be as low as 158 kg ha⁻¹ (FAO, 1991) due to low pH, and nutrient deficiencies.

Although fertilizers play a significant role in increasing crop yields, their use is still very low averaging 7.6 kg ha⁻¹ of nutrient in Tanzania (Baanante *et al.*, 1989). Low P availability is a primary constraint to bean production in Africa, and more than 50% of the crop is grown on severely P deficient soils (Wortmann and Allen, 1994). Tanzania depends on fertilizer imports to meet all of its domestic requirements. The rate of recommended P for a bean crop which is 50 kg P₂O₅ ha⁻¹ (Samki and Harrop, 1984; Semoka *et al.*, 1990) is too costly for most of the farmers who produce more than 80% of the beans consumed in the country. Further, the only fertilizer production plant in Tanzania (Tanga based, Tanzania Fertilizer Company) ceased production in 1991 due to defective machinery. On the other hand, the indigenous phosphate deposits of soft MPR found at Minjingu in the Arusha region in Tanzania, is reported to be suitable as a directly applied phosphate rock (DAPR) fertilizer on various crops (Mwambete, 1991; Van Kauwenbergh, 1991). Phosphate rock (PR) is a

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general term used to describe naturally occurring mineral assemblages that contain a high concentration of phosphate mineral. This term, PR is used to describe both unbeneficiated phosphate ore, and concentration products (Van Kauwenbergh, 1992).

Phosphorous fertilizer provides the P element required for growth in the year of application, and subsequent years. Thus, P fertilizer residual values have been recorded (Barrow, 1980; Bolland, 1993; Selles *et al.* 1995), however, reports on such effects are scanty in the literature on Tanzanian soils. Marandu *et al.* (1975) observed the residual effects of P in a pasture experiment conducted in Morogoro. Other field studies using cotton by Scaife (1968), maize by Mowo and Gama (1988), and IFDC (1991) indicated good performance of MPR compared to triple superphosphate (TSP) or double superphosphate (DSP) particularly after the first two years following phosphate application.

Although systems research (analysis) is often thought of as computer work, this approach comprises, first, an analysis of components and relationships of the system, and secondly, a synthesis phase. The synthesis phase may involve either development of systems or the more efficient use of the original system (Wright, 1971). According to Penning de Vries *et al.* (1993), systems research approach involves the identification of systems, subsystems and important processes in agricultural production. Therefore, systems research approach brings together researchers through multi disciplinary research approach, and this may lead to appropriate conclusions and recommendations. In order to come up with appropriate conclusions and recommendations, there is a need to fully understand various subsystems (components) in the system.

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Systems analysis is not an alternative to the traditional methods of research but a tool to integrate information from single-factor methods with information about other factors such as: weather, cultivar, soil characteristics and crop management which may limit crop growth. Such approach has been taken by a team of international scientists who have developed a decision support system for agrotechnology transfer (DSSAT) crop models through the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project (Jones, 1993; Uehara and Tsuji, 1993).

In an excellent review on crop simulation by Whisler *et al.* (1986) crop simulation is defined as a process by which a model acts like a real crop by gradually growing leaves, stems, roots, *etc.*, during the season, and finally predicts some final state such as biomass and seed yield. Because of magnitude of possible management x genotype x environmental interactions, traditional field experimentation has proved to be limited in its ability to identify improved crop production practices. This is especially true in the tropics where each farmer and each farm is unique, and its results are site-, season-, cultivar-, and management-specific (Nix, 1980; IBSNAT, 1990). Thus the approach of matching the crop requirements to the land characteristics through systems analysis and crop simulation is important (IBSNAT, 1990).

A number of published crop simulation models have been listed by Whisler *et al.* (1986), and Ritchie (1991 and 1994). Various levels at which crop simulation models may be applied have been identified as field, farm, regional, and national level (Thornton, 1991). Using the available models, such as those by the IBSNAT project, and the DSSAT, making simplified representations that give similar results to those of actual cropping systems (Singh,

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unpublished report 1989²) is possible. This also establishes opportunities for scientists to work in problem-solving interdisciplinary groups because of the linkages between subject matter areas (Ritchie, 1989). When models are evaluated for a specific region, they provide a powerful method for replacing much trial-and-error type experimental research (Ritchie, 1994).

Crop models are powerful tools that can be used to facilitate identification of suitable agricultural technologies. This is important for resource-poor farmers in developing countries, because they reduce time, and may reduce cost of doing repetitive experiments (Muchena, 1994). Although there has been a number of crop model simulation application studies in Africa (Keating *et al.*, 1992; Singh *et al.*, 1993; Muchena, 1994; Thornton *et al.*, 1995), there is not any documented work on use of crop modeling experiments in Tanzania. In general, there is also limited published work on crop simulation using bean crop simulation models under field conditions (Gutierrez *et al.*, 1994). Further, no field studies on bean irrigation have been reported whereby the total dry matter (TDM), plant part dry matter, leaf area index (LAI), related growth analysis, P removal from the field, and residual P effectiveness were determined under Tanzanian conditions.

Therefore the objectives of this study were: (1) To evaluate the P version of the BEANGRO crop simulation model for Tanzanian conditions for sensitivity to phosphorous response; (2) To evaluate the P uptake, partitioning and its accumulation by a bean (*Phaseolus vulgaris* L.) crop grown under different sources, and levels of P fertilizers under

²Singh, U. 1989. Introduction to modeling. Report for training program on computer simulation for crop growth and fertilizer responses. May 15-26, 1989. International Fertilizer Development Center, P.O. Box 2040, Muscle Shoals, AL. 35660.

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rainfed, and irrigated conditions; (3) To assess the growth, and yield of a bean crop as influenced by Minjingu phosphate rock (MPR) as a directly applied phosphate rock (DAPR) fertilizer, in comparison with triple superphosphate (TSP) fertilizer; (4) To assess the residual effectiveness of MPR as a DAPR fertilizer in comparison with TSP fertilizer on a bean crop grown, and yield under rainfed and irrigated conditions.

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CHAPTER 2

SIMULATION OF BEAN (*Phaseolus vulgaris* L.) YIELD AND BIOMASS RESPONSE TO PHOSPHOROUS APPLICATION UNDER TANZANIAN CONDITIONS

ABSTRACT

A field study was conducted during the 1993 and 1994 growing seasons at the Sokoine University of Agriculture farm (6° 50'S, 37° 39'E at 525 m altitude) in the Morogoro region of Tanzania. The objectives of the study were to collect a minimum data set (MDS) and evaluate the performance of a bean (*Phaseolus vulgaris* L.) crop for sensitivity to phosphorous (P) response under rainfed and irrigated conditions using the bean simulation model BEANGRO. The bean cultivar, Canadian Wonder was planted at 25 plants m⁻² in plots of 24 m² for both experiments. The experimental plots were planted in a complete randomized block design with three replications. The Minjingu phosphate rock (MPR) soft ore that could pass through a 75 - micron screen and triple superphosphate (TSP) were used. Both TSP (46% P₂O₅) and MPR (30% P₂O₅) were broadcast and incorporated in each plot at respective rates at planting. Seven treatments were used in the study as follows: 0 kg P ha⁻¹ - control; 22 kg P ha⁻¹-low rate-TSP; 22 kg P ha⁻¹-low rate-MPR; 44 kg P ha⁻¹-medium rate-TSP; 88 kg P ha⁻¹-high rate-TSP; 88 kg P ha⁻¹-medium rate-MPR; and 176 kg P ha⁻¹-high

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The crop simulation model was calibrated using Canadian Wonder cultivar data obtained from the 1993 well-fertilized (88 kg P ha^{-1} -TSP) irrigated experiment (which had the least non-limiting factors). Adjustments were made in cultivar-specific coefficients related to life cycle, pod, seed, biomass yield, seed size, and maximum leaf area index (LAI). Model validation was made by comparing model predicted with field measured data for growth, development, yield and seed yield components obtained from the 1993 and the 1994 seasons. Despite incidence of pests and diseases during the study, the model accurately predicted the occurrence of flowering, physiological maturity, pod, seed, biomass yield, and maximum LAI under irrigated conditions. The conclusion drawn from this study is that the P version BEANGRO can be used to assess growth, development and yields of a bean crop as influenced by different fertilizer P rates, planting dates, plant population, bean cultivar under the irrigated conditions in Tanzania. Results suggest that because diseases and pests are major factors in bean yield reductions, their effects need to be incorporated in the model. The model should be tested in areas with high bean production of Tanzania so as to build up confidence in the model-outputs.

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LITERATURE REVIEW

Agricultural and environmental research utilizes knowledge of specific processes within a complex system of interacting and interdependent phenomena to attempt a comprehensive understanding of the operation of the system as a whole. Currently, crop models and simulation techniques have been developed to provide comprehensive and quantitative description of the behavior of dynamic crop growth patterns (Singh *et al.*, 1985).

A model as defined by Hanks and Ritchie (1991) is a small representation of the real thing or a system of postulates, data and inferences presented as a mathematical description of an entity or state of affairs. Crop models integrate component submodels of various processes in the soil-plant-atmosphere system to provide predictions of growth and yield of crops. Thus, crop models are principal tools which bring agronomic sciences into the information age (Jones and Ritchie, 1990; Ritchie 1991, and 1994).

In the review by Whisler *et al.* (1986), crop simulation is defined as the process whereby the crop model acts like a real crop by gradually growing leaves, stems, roots, etc., during the season and finally predicts some final state such as biomass and seed yield. Model accuracy may be defined in three progressive stages (Jones *et al.*, 1987). These stages are: (I) verification process (the programming logic is compared with the programmer's intentions); (ii) calibration process (the adjustments made to model parameters so as to give the most accurate comparison between simulated results and results obtained from field measurements) and; (iii) validation process (the process by which a simulation model results are compared to field data not used previously in the development or calibration process).

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Model testing involves validation and sensitivity analyses. The purpose of validation is to obtain a measure of confidence in the model for the intended use. Sensitivity analysis refers to the process where one or more input variable such as cultivar, planting date or fertilizer type is changed while others are held constant. This answers the "what happens if...?" questions.

Use of crop simulation models in agricultural research has increased dramatically with enhancements of modeling techniques, and with improvements in microcomputers (Hanks and Ritchie, 1991). Crop simulation models enable better understanding of a systems and generate relevant and more precise data for the system(s) under study by multi disciplinary team work while solving the problem. Crop models predict crop yields sown anywhere at anytime, and have proved to be a useful tool for decision making by farmers, researchers and policy makers (Ritchie, 1986; Singh, 1989) at field, farm, regional, and national levels (Thornton, 1991; Thornton *et al.*, 1991). They have also been developed to analyze single-season (Thornton and Hoogenboom, 1994), and multiple-season experiments (Thornton *et al.*, 1995 a). Crop models can also be used in sustainability research, and assessment of environmental impact (Singh and Thornton, 1992; Bowen *et al.*, 1993; Jones *et al.*, 1993). They have also been used at national and at global level to provide quantitative estimates (Adams *et al.*, 1990; Rosenzweig and Parry, 1994).

The CERES (Crop-Environment Resource Synthesis)-family models have been used more widely than other crop models. This has been mainly due to the functions which can be performed by these models as outlined by Adams *et al.* (1990). CERES-Maize has been used to study various crop aspects in sub-Saharan Africa. Using the CERES-Maize crop

model, Keating et al. (1995) showed that the model could provide accurate predictions of maize yields under different management regimes. They used the model to predict the effect of different maize crop in the region of Malawi. The model was used in the study conducted by Keating et al. (1995) which can develop a composite maize yield model.

In Malawi, the model was used to predict the effect of different management regimes on planting date, fertilizer application, and variety selection, and to predict the effect of different management regimes replicated over multiple years. The model was used to predict the effect of different management regimes on land evaluation, soil fertility, and crop management strategies. The model was used to predict the effect of different management regimes on crop yield, as well as on the environment. The model was used to predict the effect of different management regimes on the region of Malawi. The model was used to predict the effect of different management regimes on decision/policy making. (Keating et al. 1995b).

In a study conducted in Nigeria, the CERES-Maize model was used to predict the effect of different management regimes on observed yield (Jas et al. 1995). The model was used to predict the effect of different management regimes on the station at Rubona, in Nigeria.

model, Keating *et al.* (1991), and McCown *et al.* (1991) working in Eastern Kenya made accurate predictions of grain yield under a wide range of water, N, and crop management regimes. They were also able to assess the residual effects of fertilizer application on the maize crop in the previous season. Keating and Wafula (1992) used the CERES-Maize model in the study conducted at the Katumani Research Station to identify the resource constraints which can develop under high plant population which limit the leaf size of the open-pollinated composite maize cultivar, Katumani composite B.

In Malawi, Singh *et al.* (1993) used the CERES-Maize model to collect information useful on planting time periods, optimum plant densities, nitrogen fertilizer management, variety selection, and the economics of fertilizer use by carrying out simulation experiments replicated over many different seasons. In a different study, done on a regional basis, CERES-Maize was linked with geographic information system (GIS) data, and an automated land evaluation system. From this study presenting suggestions concerning different management strategies such as time, and amount of nitrogen fertilizer applications was possible, as well as quantifying the weather-related risks of maize production in the central region of Malawi. Furthermore, information obtained from this study was shared among decision/policy makers, researchers, and extension personnel (IFDC, 1994; Thornton *et al.*, 1995b).

In a study at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, the CERES-Maize model predicted maize yields that were within 10% of the observed yield (Jagtap *et al.*, 1993). However, in a study conducted at a small research station at Rubona, in Rwanda, the CERES-Maize model did not accurately predict grain yield

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of the local maize cultivar because of poor data collection (Mbabaliye and Wojtkowski, 1994). The CERES-Maize model has been used to estimate how climate changes and increasing levels of carbon dioxide may alter yields in the world's crops. Effects of change in climate on crop yields were found to be more adverse in developing countries than developed countries (Muchena, 1994; Rosenzweig and Parry, 1994).

Most of the crop simulation models currently available have been listed by Whisler *et al.* (1986), and Ritchie (1991 and 1994). The latest released DSSAT crop simulation model is BEANGRO (Hoogenboom *et al.*, 1994). BEANGRO is a versatile, user friendly simulation model for bean (*Phaseolus vulgaris* L.) crop. The model has a flexible user interface that allows researchers to compare simulation results with data measured from the field, and conduct sensitivity analysis (Hoogenboom *et al.*, 1994). The model responds to the environmental variables such as soil profile characteristics, rainfall, solar radiation, minimum and maximum temperatures. Cultivar coefficients, characteristics, and crop management strategies are also very important. These variables constitute the minimum data required to run the DSSAT crop models (Ritchie and Dent, 1994).

The BEANGRO crop simulation model operates at daily time steps, and simulates bean crop growth, and development from the date of sowing until harvest maturity (Hoogenboom *et al.*, 1994). The model incorporates features that facilitate its use by dry bean researchers whose primary activity is not modeling *per se* (Hoogenboom *et al.*, 1991). BEANGRO predicts total dry matter (TDM) production (kg ha^{-1}), leaf area index (LAI), developmental stages, seed size, and seed yield (kg ha^{-1}). The present BEANGRO version was developed by an interdisciplinary research team through numerous changes of grain

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legume models such as SOYGRO for soybean (*Glycine max* (L.) Merr.), and PNUTGRO for peanut (*Arachis hypogea* L.) (Boote *et al.*, 1989; Hoogenboom *et al.*, 1992; Hoogenboom *et al.*, 1993). Details on data collection, input and simulation output files, and sensitivity analysis are given by Hoogenboom *et al.* (1994), and Tsuji *et al.* (1994).

Globally, there is little published work on crop simulation using bean crop models under field conditions (Gutierrez *et al.*, 1994). The few studies that have been conducted include that at CIAT, Cali, Colombia using an earlier bean model version to study drought tolerance, and potential drought adaptation mechanisms of bean (Hoogenboom *et al.*, 1987). In the USA the model has been used to study the impact of potential climate change on bean production (Curry *et al.*, 1990; Lal *et al.*, 1993). The model has also been used by Acosta-Gallegos and White (1995) to estimate the length of the crop growing season in Mexico. The BEANGRO model has also been used to evaluate the responses to cultivar differences for production in tropical environments (White *et al.*, 1995). Further, the international bean modeling nurseries have been established at several sites in Canada, the USA, Central and South America (Hoogenboom *et al.*, 1994). Similar nurseries are being established in several bean growing regions in Africa (Smithson and Grisley, 1992).

To have the ideal model of the behavior of the soil and plant P, a full description of the cycling processes is required. This requires an understanding of all important physical, chemical, and biological processes influencing the various forms of P in each component of the cycle. The complexity of P chemistry in the soil, and plants is reflected by its many forms that are distinguished in a comprehensive model of soil and plant P given

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Details of P nutrient uptake, translocation and assimilation in plants are discussed in details in Chapters 3 and 4. Phosphorous deficiency decreases photosynthetic rate per unit leaf area (Freedden *et al.*, 1989; Lauer *et al.*, 1989; Qui and Israel, 1992; Rao and Terry, 1989), leaf area to weight ratio (Israel and Rufty, 1988), and nitrogen fixation in soybeans (Israel, 1987; Sa and Israel, 1995). Other investigations show that metabolic reactions that influence the number of pods formed, and those affecting weight per seed have different P concentration optima (Grabau *et al.*, 1986). Recent findings indicate that there is a large genetic variation for P deficiency in bean cultivars, small seeded (Mesoamerican genotypes) being more responsive to applied P than large-seeded (Andean genotypes) which have a superior P efficiency under low available P (Yan *et al.*, 1995 a, b).

A phosphorous submodel for the IBSNAT crop models has been developed at IFDC, and its operation is described in the IBSNAT network report (IBSNAT, 1990), and IFDC working manual (IFDC, 1992; Bowen 1994, unpublished). The submodel simulates the processes of adsorption and desorption of P, organic P turnover (immobilization and mineralization), and dissolution of soluble fertilizer P. The rates of each of the soil P processes are assumed to be affected by the size of the labile P pool and prevailing soil, water, and temperature conditions. The P uptake process is simulated as a function of root length density, soil water content, plant P demand, and soil N and P concentrations. Plants absorb P from the labile pool. The model is sensitive to methods of P fertilizer application.

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This P submodel, like the present soil water and N balance model, has been coupled to the plant growth routines of the BEANGRO crop simulation model. If the P submodel is switched on, P, N and water balance models automatically function (IFDC, 1992). Therefore, the actual dynamic section of the BEANGRO version used in this study consists of five components. These are crop development, carbon balance, water balance, N balance (Hoogenboom *et al.*, 1994), and P balance simulations (Dr. W.T. Bowen, 1995, personal communication). This section operates on daily time steps from planting to harvest maturity.

A number of models dealing primarily with P residual effects have been proposed (Black, 1993). In the P model coupled to the BEANGRO crop model there are ten subroutines in the current P-model, and these are: SOILPI (initializes soil inorganic P pools at the beginning of simulation), OCNPI (initializes organic pools for C, N, and P at the beginning of simulation), FPLACE (fertilizer placement for N and P on days of fertilizer application), PBAND (effective band size calculation, if fertilizer applied in band), PDISS (phosphate rock dissolution, if PR is applied), PUPTAK (P uptake on daily growth basis), PFACTO (P deficiency factors on daily growth basis), ORGANIC (organic N and P cycling, on daily basis), PCHEM (calculates the rates of movement between the different inorganic P pools on daily basis, then updates each pool based on the calculated rates), and PTHERM (P adsorption isotherm).

Singh *et al.* (1985) stated that the success of agrotechnology transfer rests, in essence, with the individual farmer. The two basic reasons for failures in agrotechnology transfer are: (I) mismatches between the environmental requirements of a technology and the

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Although there has been a number of crop model simulation application studies in Africa (Keating *et al.*, 1991 and 1992; Singh *et al.*, 1993; Muchena, 1994; Thornton *et al.*, 1995b), there is no documented work on the use of crop modeling experiments in Tanzania. This has mainly been due to (I) the lack of adequate training, and involvement of Tanzanian researchers and policy makers in model applications, (ii) lack of appropriate models for the local conditions in Tanzania, (iii) lack of data (such as cultivar and soil characteristics) for calibrating and validating the already developed model components and (iv) lack of financial support for model development and application in Tanzania. Furthermore, N is the nutrient to which most attention has been devoted, and there are no reported P simulation studies using DSSAT crop models.

Therefore, the specific objectives of this study were: (I) To conduct a two year field experimental work on beans (*Phaseolus vulgaris* L.), and collect the minimum data set (MDS) required for evaluation of the P version of the BEANGRO bean simulation model for Tanzanian conditions; (ii) To evaluate the performance of a bean crop for sensitivity to phosphorous response under rain-fed, and irrigated conditions using the P version BEANGRO crop simulation model for Tanzanian conditions.

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MATERIALS AND METHODS

Rainfed Experiment

This study was conducted at Sokoine University of Agriculture (SUA) farm (6° 50'S, 37° 39'E at 525 m altitude), in Eastern Tanzania, on sandy loam soils during the March to June rainy seasons of 1993 and 1994. The rainfall pattern on site is bimodal with a long-season from March to June, and a short-season from October to December with an average rainfall of 900 mm.

Prior to the initiation of the experiment, the site lay under natural vegetation (weeds) for three years. Tillage was done with a disk plow two weeks before planting in the first season. Plots were prepared using hand hoes in both seasons. The amount of natural vegetation incorporated during the land preparation was estimated as described in Form H of Technical Report 2 (IBSNAT, 1990). The slope at the site was estimated to be 0-2%, according to Ritchie *et al.* (1990). Soils for analysis were collected from a composite of 12 cores to a depth of 12 cm from each treatment at pre-planting, and post-harvest periods, mixed and bulked for analysis. Pre-plant soil physical, and chemical characteristics for each experiment are shown in Table 2.1. Tables 4.2a and 4.2b show soil chemical characteristics after fertilizer application in the 1993 and the 1994 seasons.

Since the model requires a data set on climate, the daily weather data for the two seasons were collected as shown in Figs. 2.1 to 2.3, and Appendix 2a. Longitude, latitude, daily solar radiation (MJ m^{-2}), minimum, and maximum temperatures ($^{\circ}\text{C}$) were manually recorded from the meteorological station at SUA.

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Appendix 1a.

The meteorological station was 400 m from the experimental site, therefore, rain-gauges were installed, and rainfall records (mm) were collected daily on-site.

Soil inputs such as albedo, fraction (SALB), evaporation limit, cm (SLU1), drainage rate, fraction day⁻¹ (SLDR), runoff curve (SLRO), mineralization factor, 0-1 factor, (SLNF), photosynthetic factor, 0-1 (SLPF), root growth factor, 0-1 (SRGF), and saturated hydraulic conductivity, macropore, cm h⁻¹ (SSKS) were estimated using methods described by Ritchie *et al.* (1990). Crop residue dry weight (kg ha⁻¹) was determined as described by IBSNAT (1990). Using the growing maize (*Zea mays* L.) crop, drained upper limit, cm³ cm⁻³ (SDUL), saturated upper limit, cm³ cm⁻³ (SSAT) and lower limit, cm³ cm⁻³ (SLLL) were determined as described by IBSNAT (1990). However, the values of field-measured soil water availability determined for SDUL, SSAT and SLLL were found to deviate significantly from the literature values for soils with similar characteristics (Ratliff *et al.*, 1983). Therefore, a computer program SWLIM (J.T. Ritchie, 1995, personal communication) was used to calculate these values using the sand, clay percentage, and bulk density values determined for each soil layer (Table 2.2a). Bulk density (SLDM) values were predicted based on the method described by Rawls (1983). The soil profile descriptions for the site are shown in Appendix 1a.

Table 2.1. General
experimental site

Soil characterist

Moisture (%)^a
pH H₂O
Organic Carbon (%)
Nitrogen (%)
Bray-I P (ppm)
Bulk density (cm³)
Sand (%)
Silt (%)
Clay (%)
Textural Class
Classification

Exchangeable cation
Ca (meq 100g⁻¹ soil)
Mg "
K "
Al "
ECEC "
Al saturation (%)
Drainage class
Permeability
Color

^a Volumetric mois

Table 2.1. General pre-plant soil characteristics of 0-12 cm soil layer at blocks A and B at the experimental sites.

Soil characteristic	Experimental Site	
	Rainfed	Irrigated
Moisture (%) ^a	13.09	15.23
pH:H ₂ O	4.60	5.50
Organic Carbon(%)	0.83	2.27
Nitrogen (%)	0.04	0.09
Bray-I P(ppm)	1.18	2.83
Bulk density (cm ³ /cm ³)	1.17	1.39
Sand(%)	60	55
Silt (%)	20	24
Clay (%)	20	21
Textural Class	Sandy loam	Sandy clay loam
Classification	Isothermic Aridic tropustic	Isothermic Typic tropustic
Exchangeable cations:		
Ca (meq 100g ⁻¹ soil)	2.20	2.70
Mg “	1.31	0.80
K “	1.33	1.45
Al “	1.03	1.05
ECEC “	5.87	6.00
Al saturation (%)	17.54	17.50
Drainage class	Moderate	Poor
Permeability	Moderate	Poor
Color	Reddish	Dark grayish brown

^a Volumetric moisture content

Table 2.2a. Soil
rainfed experiment

*SUMO930000 MGR
#SITE DOX
#MOROSORO TAN
#SDM SALB SL
2.5YR 0.12 e
#SLB SLPH SL

10 Ap 0.1
20 Ap 0.1
30 E 0.1
40 AB 0.1
50 B1 0.1
60 B2 0.1
70 B2 0.1
80 B2 0.1
90 B3 0.1
100 B3 0.1

PHOSPHORUS DATA
#SLB SLPH SL

10 3.50 2.7
20 3.30 2.7
30 3.33 2.4
40 2.51 2.7
50 2.51 2.7
60 2.51 2.7
70 1.59 2.7
80 1.53 2.7
90 1.42 2.7
100 1.41 2.7

SLB=Soil layer den
SDU=Drained upper
SLPH=Root growth, fa
density, moist g
SLN= Total nitroge
SLPH= Organic P mg
et al. (1994).

In both seas
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Table 2.2a. Soil profile characteristics for the isohyperthermic, aridic tropustic Oxisol at the rainfed experiment.

*SUMO930002 MOROGORO, TZ SALO 100 OXISOL ISOHYPERTHEMIC, ARIDIC TROPUSTIC														
#SITE		COUNTRY		LAT		LOG		SCS FAMILY						
MOROGORO		TANZANIA		-6.5		37.3		REDDISH BROWN SAND LOAM						
#	SCOM	SALB	SLUI	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE	SRGP			
	2.5YR	0.12	6.0	0.50	84.0	1.00	1.00	IB001	IB001	IB001	IB003			
#	SLB	SLMH	SLLL	SDUL	SLDA	SLRF	SLKS	SLDM	SLOC	SLCF	SLSI	SLCY	SLNI	SLHW
	10	Ap	0.091	0.227	0.382	1.000	16.56	1.55	1.13	60.0	20.0	20.0	0.06	4.56
	20	Ap	0.066	0.202	0.382	0.841	16.56	1.55	1.13	65.0	30.0	15.0	0.06	4.50
	30	E	0.104	0.240	0.399	0.499	16.16	1.50	0.76	65.0	15.0	30.0	0.05	5.38
	40	AB	0.125	0.261	0.365	0.338	16.56	1.60	0.76	53.0	13.0	24.0	0.06	5.50
	50	B1	0.088	0.224	0.382	0.166	6.98	1.55	0.70	65.0	13.0	22.0	0.05	5.69
	60	B2	0.165	0.301	0.347	0.134	5.98	1.65	0.70	55.0	10.0	35.0	0.04	4.59
	70	B2	0.053	0.189	0.417	0.019	5.98	1.45	0.40	68.0	15.0	17.0	0.04	4.23
	80	B2	0.159	0.295	0.417	0.016	16.55	1.45	0.33	40.0	24.0	36.0	0.05	5.14
	90	B3	0.154	0.290	0.434	0.012	5.99	1.40	0.33	35.0	30.0	35.0	0.05	4.46
	100	B3	0.089	0.225	0.472	0.003	5.99	1.29	0.30	38.0	22.0	20.0	0.03	4.61
! PHOSPHORUS DATA														
#	SLB	SLPX	SLPT	SLPO	SLCA	SLAL	SLFE	SLMN	SLBS	SLPA	SLPB	SLKE	SLMG	SLNA
	10	3.50	270	120.0	1.77	1.5	3.20	-99	-99	-99	-99	1.6	5.60	0.19
	20	3.30	270	120.0	1.59	1.5	3.20	-99	-99	-99	-99	1.6	5.70	0.19
	30	3.33	242	120.0	1.45	1.4	3.00	-99	-99	-99	-99	1.4	2.80	0.22
	40	2.51	170	80.0	1.31	1.3	2.87	-99	-99	-99	-99	1.4	2.60	0.22
	50	2.51	170	80.0	1.24	1.3	2.86	-99	-99	-99	-99	1.4	2.80	0.22
	60	2.51	170	80.0	1.07	1.3	2.20	-99	-99	-99	-99	0.4	2.30	0.22
	70	1.59	170	80.0	0.61	1.3	2.20	-99	-99	-99	-99	0.4	2.30	0.16
	80	1.53	75	50.0	0.33	1.3	1.29	-99	-99	-99	-99	0.4	1.30	0.16
	90	1.42	75	50.0	0.34	1.3	1.87	-99	-99	-99	-99	0.4	1.20	0.16
	100	1.41	75	50.0	0.34	1.2	1.10	-99	-99	-99	-99	0.4	1.20	0.16

SLB=Soil layer depth (cm), SLMH=Master horizon, SLLL=Lower limit water content($\text{cm}^3 \text{ cm}^{-3}$) SDUL=Drained upper limit water content ($\text{cm}^3 \text{ cm}^{-3}$), SLDA= Saturated water content ($\text{cm}^3 \text{ cm}^{-3}$), SLRF=Root growth factor (0-1.0), SLKS=Sat. hydraulic conductivity, macropore cm h^{-1} , SLDM=Bulk density, moist (g cm^{-3}), SLOC=Organic carbon (%), SLFC= Sand (%), SLSI=Silt (%) SLCY=Clay(%) SLNI= Total nitrogen (%), SLHW=pH (water), SLPX= P extractable (mg kg^{-1}) SLPT=Total P (mg kg^{-1}) SLPO= Organic P (mg kg^{-1}), SLCA= Ca g kg^{-1}). Other variables not measured are defined by Tsuji et al. (1994).

In both seasons, pre- and post-harvest soil chemical characteristics were taken seven days before planting. However, during the 1994 growing season, pre-planting soil characteristics were taken 365 days from the time the P treatments were applied. Post-harvest soil characteristics were taken seven days after harvest. The methods used for soil analyses were: mechanical analysis - hydrometer (Day, 1965); and pH measurements using

1:2.5, soil water

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Technical Report

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22 kg P ha⁻¹-low ra

kg P ha⁻¹-medium ra

1:2.5, soil:water suspension by use of a pH electrode; N - micro Kjeldahl (Juo, 1979); available P by Bray I i.e., 0.025N HCl+0.03N NH_4F extractant (Bray and Kurtz, 1945), organic carbon by Walkley and Black (1965). Exchangeable cations (Ca, K, Mg, etc.) were extracted in 1N NH_4OAc and measured by atomic absorption spectrophotometer. Extractable Al by 1N KCl was determined colorimetrically.

Plots were sown with a dibble, placing one seed per hole at a spacing of 40 cm between rows and 10 cm within rows on April 4, 1993, and April 14, 1994 at the depth of about 2.5 cm. The spacing gave a plant population of 250,000 ha^{-1} or 25 plants m^2 . Experimental plots were prepared as recommended for the physical dimensions of a designated minimum data set (MDS) for a bean crop (IBSNAT, 1990). Thus, each plot was 15 m long with four rows resulting in a plot size of 24.0 m^2 with rows running from East to West across the slope. During the 1993 season the experiment had two blocks (A and B), in which each block had three replications, and each replication consisted of seven treatments (plots). Only block B was used to collect data for evaluation of the BEANGRO model in both seasons. Block B from each experiment was also used to assess the influence of annual applied P on bean growth, and yield (refer to Chapter 4 for details).

The experimental design and data collection procedures were as described in the Technical Report 1 (IBSNAT, 1988), and Technical Report 2 (IBSNAT, 1990). The experiments were sown in a complete randomized block design (CRBD). The seven treatments used in the study were as follows: 0 kg P ha^{-1} - control; 22 kg P ha^{-1} - low rate-TSP; 22 kg P ha^{-1} - low rate-MPR; 44 kg P ha^{-1} - medium rate-TSP; 88 kg P ha^{-1} - high rate-TSP; 88 kg P ha^{-1} - medium rate-MPR; and 176 kg P ha^{-1} - high rate-MPR. The MPR ore that could pass

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Leaf area

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meter model LI-C

10,000 cm². At c

leaf number on

through a 75 - micron screen was used. The commercially distributed PR fertilizer was obtained from the Minjingu Phosphate Company (MIPCO) based in the Arusha Region. Both TSP (46% P_2O_5), and MPR (30% P_2O_5) were broadcast, and incorporated in each plot at rates prescribed by treatments at planting. The commercially available, and most commonly grown bean cultivar "Canadian Wonder" was used in this study. This is an Andean cultivar with determinate bush growth habit (I), and intermediate photoperiodic response (White *et al.*, 1992; Sexton *et al.*, 1994).

To prevent yield reductions from inadequate levels of nitrogen to which the model is sensitive, 80 kg N ha⁻¹ in the form of urea was split into two equal applications. It was side dressed at planting, and again at the flowering (R_1) stage in all plots. Other standard agronomic practices were used to obtain optimum growth under protected conditions. These included the control of the major insects, mainly foliar beetle (*Oothea benningseni* (Weise)) using the insecticide "Karate" at 33.0ml 20L⁻¹ H₂O. Dithane-M45 was applied at 250g 100⁻¹ liters of water mainly to control bean rust (*Uromyces appendiculatus* (Pers.)), white mold (*Sclerotinia sclerotiorum* (Lib.) de Bary), and angular leaf spot (*Phaeoisariopsis griseola* (Sacc)). Spraying was done at seven-day intervals, starting at 95 % crop emergence (V_2) until at R_6 . Weeds were controlled by hoeing between rows and hand pulling within rows.

Leaf area index (LAI) values were determined at each harvest time by photocopying all leaves from the harvested plants, cutting out the leaf images, and using a portable leaf area meter model LI-COR 3000 to determine the leaf areas in cm² from a subtended land area of 10,000 cm². At crop establishment growth stage (V_2), five plants were tagged per plot, and leaf number on main stem were counted at every sampling time. At R_3 growth stage, leaf

production on the

number plant⁻¹ of

There were

were done at V

basis (per plot) to

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stage most plants

At each harvest, the

plot. This gave 1

The record

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in 1994. All grain

removing all debris

comparison with

Details on

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procedures, and L

this experiment was

production on the main stem reached a maximum number. After this stage, the average leaf number plant⁻¹ plot⁻¹ was determined.

There were four biomass harvests before the final harvest at (R₉) maturity. These were done at V₃, R₁, R₃, and R₇ growth stages. Visual assessments were made on a daily basis (per plot) to record days to different growth stages as described by Fehr *et al.* (1971), and Nuland and Schwartz (1989). The key for bean growth stages used in this study is shown in Appendix 3. Final harvest was done at R₉ (harvest maturity) growth stage. At this growth stage most plants had more than 80% of pods yellowing, and less than 15% of green leaves. At each harvest, plants were hand pulled from a 1.25 m long in the two central rows of each plot. This gave 1.0 m² of harvested area.

The recommended biomass, and final harvest procedure followed the description in Technical Report 2 (IBSNAT, 1990). The crop was harvested 65 DAP in 1993 , and 72 DAP in 1994. All grain yields were reported as marketable seed, i.e., seeds not damaged. After removing all defective seeds, the seed weight was adjusted to zero moisture content for comparison with simulated values.

Irrigated Experiment

Details on location, altitude, associated temperature regimes, solar radiation, rainfall (mm), experimental design, spacing, plot size, treatments, crop management, sampling procedures, and LAI determinations are as reported under the rainfed experiment. However, this experiment was conducted in the area near the SUA crop museum, about 800 m from the

rainfed experime

of May through

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rainfed experimental site (for the accessibility of irrigation water), during the growing seasons of May through August 1993, and 1994. Rows ran north to south across the slope. This site contained a sand clay loam type soil, and had lain fallow during the previous two years. The soil inputs used for the crop model i.e., drained upper limit (SDUL), lower limit (SLL), saturated upper limit (SSAT), pH, etc., are shown in Table 2.2 (b). Physical and chemical characteristics were determined as explained in the previous experiment. Soil profile description at the site is as shown in Appendix 1b.

Table 2.2b. Soil
irrigated site

*SOM0930001	M:
ESITE	CO
MOROGRORO	
ISOHYPERTHEMIC,	
# SOM	SALE
2.5YR	0.13
# SLB	SUMH
10	Ap
20	Ap
30	AB
40	B1
50	B1
60	B2
70	B2
80	B2
90	B3
100	B3

#	PHOSPHORUS
# SLB	SLPX
10	4.33
20	4.10
30	3.57
40	2.90
50	2.00
60	1.47
70	2.05
80	1.64
90	1.71
100	1.54

SLB=Soil layer
SDSL=Drained upper
SLPX=Root growth
density, moist
SLAT=Total nitrogen
SLPO=Organic P (N
et al. (1994).

Hoes were
on May 28 for
Planting was done
development of the
the 1993 season

Table 2.2b. Soil profile characteristics for the isohyperthermic, typic tropustic Alfisol at the irrigated site.

*SUMO930001	Morogoro,TZ	SACLLO 100	ALFSOL, ISOHYPERTHEMIC, TYPIC TROPUSTIC											
@SITE	COUNTRY	LAT	LONG SCS FAMILY											
MOROGRORO	TANZANIA	-6.5	37.3	DARK	GRAYISH	BROWN	SAND	CLAY	LOAM					
ISOHYPERTHEMIC,TYPIC TROPUSTIC														
@ SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE	SGRP				
2.5YR	0.13	6.0	0.35	84.0	1.00	1.00	IB001	IB001	IB001	IB003				
@ SLB	SLMH	SLLL	SDUL	SLSA	SLRF	SLKS	SLDM	SLOC	SLCF	SLSI	SLCY	SLNI	SLHW	SLHB
10	Ap	0.081	0.217	0.434	1.000	5.01	1.40	2.27	55.0	24.0	21.0	0.09	5.43	5.30
20	Ap	0.097	0.233	0.382	0.819	6.98	1.55	2.27	57.0	23.0	20.0	0.09	5.09	5.20
30	AB	0.102	0.238	0.382	0.268	7.08	1.55	1.15	59.0	18.0	23.0	0.08	4.25	5.20
40	B1	0.101	0.237	0.382	0.268	5.01	1.55	1.64	58.0	24.0	22.0	0.07	5.03	5.00
50	B1	0.082	0.218	0.399	0.138	5.01	1.50	1.80	58.0	24.0	18.0	0.07	5.03	5.00
60	B2	0.129	0.265	0.295	0.128	5.01	1.50	1.80	58.0	23.0	19.0	0.07	5.04	5.00
70	B2	0.096	0.232	0.382	0.128	5.02	1.55	1.60	59.0	20.0	21.0	0.09	5.13	5.05
80	B2	0.056	0.192	0.451	0.128	6.99	1.35	1.60	48.0	42.0	10.0	0.06	4.83	5.00
90	B3	0.056	0.192	0.451	0.100	6.25	1.35	0.55	48.0	42.0	10.0	0.05	4.80	5.10
100	B3	0.056	0.192	0.451	0.100	6.84	1.35	0.55	48.0	42.0	10.0	0.05	4.61	5.10
! PHOSPHORUS DATA														
@ SLB	SLPX	SLPT	SLPO	SLCA	SLAL	SLFE	SLMN	SLBS	SLPA	SLPB	SLKE	SLMG	SLNA	SLSU
10	4.33	360	280	2.03	1.10	1.20	-99	-99	-99	-99	0.60	2.80	0.71	-99
20	4.10	360	280	2.01	1.10	1.20	-99	-99	-99	-99	0.60	2.50	0.71	-99
30	3.57	309	30	1.94	0.80	1.60	-99	-99	-99	-99	0.30	1.50	0.61	-99
40	2.91	309	30	1.93	0.80	1.10	-99	-99	-99	-99	0.40	1.30	0.61	-99
50	2.02	309	30	1.93	0.30	1.10	-99	-99	-99	-99	0.30	1.10	0.61	-99
60	1.47	309	30	1.64	0.30	1.20	-99	-99	-99	-99	0.30	1.10	0.61	-99
70	2.05	309	30	1.04	0.30	1.20	-99	-99	-99	-99	0.30	1.10	0.61	-99
80	1.64	143	40	0.94	0.30	1.10	-99	-99	-99	-99	0.30	1.10	0.65	-99
90	1.71	143	40	0.84	0.30	1.10	-99	-99	-99	-99	0.30	1.00	0.65	-99
100	1.54	133	40	0.52	0.30	1.00	-99	-99	-99	-99	0.30	1.00	0.65	-99

SLB=Soil layer depth (cm), SLMH=Master horizon, SLLL=Lower limit water content (cm³ cm⁻³)
SDUL=Drained upper limit water content (cm³ cm⁻³), SLDA= Saturated water content (cm³ cm⁻³),
SLRF=Root growth factor (0-1.0), SLKS=Sat. hydraulic conductivity, macropore cm h⁻¹, SLDM=Bulk
density, moist (g cm⁻³), SLOC=Organic carbon (%), SLFC= Sand (%), SLSI=Silt (%) SLCY=Clay(%)
SLNI= Total nitrogen (%), SLHW=pH (water), SLPX= P extractable (mg kg⁻¹) SLPT=Total P (mg kg⁻¹)
SLPO= Organic P (mg kg⁻¹), SLCA= Ca g kg⁻¹). Other variables not measured are defined by Tsuji
et al. (1994).

Hoes were used to prepare the experimental plots in both seasons. Sowing was done on May 28 for the 1993 growing season, and on May 8 for the 1994 growing season. Planting was done at the end of the 1993 long-rain season. To ensure rapid and complete development of the root system, pre-plant irrigation was used as shown in Appendix 4b for the 1993 season experiment. Irrigation water was provided using portable sprinklers 1.5 m

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above the soil surface. The amount of water applied was measured using the flow meter located at the experimental site. Irrigation water was applied late in the evenings when water supply was at maximum, while evapotranspiration, and windshift were minimal. The bean crop was used as an indicator of the time to irrigate. Irrigation water was applied when the color of the upright leaves changed from light green to a pronounced dark green as described by Thung (1991).

Water was applied within two to three days following this color change. Day of the year (date), amount of water applied (mm), and crop growth stage at which irrigation was applied in both seasons are shown in Appendices 4 a and 4 b. Water was pumped from the nearby river to the storage reservoir. From there, water was conveyed to the flow meter by gravity at the site through the pipe, and then to the respective sprinklers for application. The irrigation system was installed with sprinkler heads placed in the rectangular grids to irrigate the entire block at the same time. This was moved accordingly within the block so as to make sure that when water was applied, the area receiving the least amount of water was adequately irrigated to provide good crop growth.

Irrigation efficiency was calculated as defined by the On-Farm Irrigation Committee of the American Society of Agricultural Engineers (ASAE, 1978), i.e., the ratio of the volume of water that is used to the volume of irrigation water applied, expressed as:

$$e_i = V_b/V_f$$

where:

e_i = the irrigation efficiency

V_b = the volume of water used

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1993 season). The

V_f = the volume of water delivered to the field.

Irrigation efficiency for the sprinkler irrigation system used was determined by measuring the application depths with catch cans (buckets). Irrigation water was applied, and at the end of the determined period the total amount of water in the catch buckets was regarded as the volume of water used (V_b), and the amount of water registered by the flow-meter during the irrigation session was taken as the volume of water delivered to the field (V_f). To increase the application efficiency, the irrigations were small so as to avoid the soil profile being filled. This prevented deep percolation, and surface runoff was minimized. The crop was harvested 75 DAP in 1993, and 72 DAP in the 1994 season.

Prior to land preparation for the second crop of the 1994 season, experimental plots had grown lots of weeds in both experiments. These weeds were killed by the use of herbicide glyphosate (at 2.2 kg ai ha⁻¹) four weeks before the plots were prepared. During the land preparation the decomposing organic matter was incorporated in the soil.

Data Input

General input and output file structures used for crop simulation in this study are as outlined by Tsuji *et al.* (1994). The soil profile characteristics at the two sites were entered in FILES as shown in Table 2.2a for the rainfed and Table 2.2b for the irrigated site. Table 2.3 shows one of the main files, referred to as FILEX which documents the inputs of the model for a particular season and location (in this case for irrigated experiment during the 1993 season). The daily solar radiation, maximum and minimum air temperature, and rainfall

were entered in

are illustrated in

Appendices 2a

used for the eva

were entered in file FILEW (Table 2.4). For this example only the months of May and June are illustrated for the 1993 season. Details on daily weather characteristics are shown in Appendices 2a and 2b. Canadian Wonder bean cultivar genetic coefficients estimated and used for the evaluation of the bean model were entered in FILEC (Table 2.5).

Table 2.3. Example of input file (SUMO9301.BNX) used to run bean model BEANGRO.

*EXP.DETAILS: PHOSPH-BEAN 1993 IRRIGATED EXPERIMENT AT MOROGORO, TANZANIA
 ! THE EXPERIMENTAL DATA FOR THE 1993 SEASON WERE PROVIDED BY
 ! CORNEL L. RWEYEMAMU OF SOKOINE UNIVERSITY OF AGRICULTURE, TANZANIA
 ! THROUGH DR. J.T. RITCHIE, BRIAN D. BAER (MSU) and DR. W.T. BOWEN (IFDC), USA.

TREATMENTS*-----FACTOR LEVELS-----**

@N	R	O	C	NAME	CU	FL	SA	IC	MP	MI	MF	MR	MC	MT	ME	MH	SM
01	1	1	1	0 KgP/ha (CONTROL) 93/IR	1	1	1	1	1	1	1	1	0	0	0	0	1
02	1	1	1	22 KgP/ha TSP 93/IR	1	1	1	1	1	1	2	1	0	0	0	0	1
03	1	1	1	22 KgP/ha MPR 93/IR	1	1	1	1	1	1	3	1	0	0	0	0	1
04	1	1	1	44 KgP/ha TSP 93/IR	1	1	1	1	1	1	4	1	0	0	0	0	1
05	1	1	1	88 KgP/ha TSP 93/IR	1	1	1	1	1	1	5	1	0	0	0	0	1
06	1	1	1	88 KgP/ha MPR 93/IR	1	1	1	1	1	1	6	1	0	0	0	0	1
07	1	1	1	176KgP/ha MPR 93/IR	1	1	1	1	1	1	7	1	0	0	0	0	1

***CULTIVARS**

@C CR INGENO CNAME

1 BN IB0014 Canadian Wonder+

***FIELDS**

@L	ID	FIELD	WSTA	FLSA	FLOB	FLDT	FLDD	FLDS	FLST	SLTX	SLDP	ID_SOIL
1	SUMO0001	SUMO9301	-99	0	SU000	00000	00000	00000	00000	SACILLO	100	SUMO930001

***INITIAL CONDITIONS**

@C	PCR	ICDAT	ICRT	ICND	ICRN	ICRE
1	FA	93073	1	-99	1.00	1.00

@C	ICBL	SH2O	SNH4	SNO3	SAEX
1	10	0.222	2.5	3.5	4.33
1	20	0.282	2.5	2.8	4.10
1	30	0.256	2.0	2.8	3.57
1	40	0.216	2.0	2.8	2.91
1	50	0.197	2.0	2.8	2.02
1	60	0.251	1.5	2.8	1.47
1	70	0.258	1.5	2.8	2.05
1	80	0.229	1.5	2.8	1.64
1	90	0.237	1.5	2.8	1.71
1	100	0.222	1.5	2.8	1.54

***PLANTING DETAILS**

@P	PDATE	EDATE	PPOP	PPOE	PLME	PLDS	PLRS	PLRD	PLDP	PLWT	PAGE	PENV	PLPH
1	93148	93158	25.0	25.0	S	R	40	0	1.0	55	-99	-99	1.0

***IRRIGATION AND WATER MANAGEMENT**

@I	EFIR	IDEP	ITHR	IEPT	IOFF	IAME	IAMT
1	0.63	-99	-99	-99	R7	-99	-99

@I IDATE IROP IRVAL

1	93146	IR004	31.5
1	93147	IR004	27.8
1	93152	IR004	33.8
1	93154	IR004	50.0
1	93161	IR004	30.0
1	93162	IR004	27.5
1	93168	IR004	21.1
1	93174	IR004	21.1
1	93180	IR004	28.2
1	93181	IR004	31.5
1	93182	IR004	20.6
1	93187	IR004	21.1
1	93191	IR004	21.1
1	93195	IR004	24.5
1	93198	IR004	24.5
1	93204	IR004	20.8
1	93208	IR004	21.7
1	93214	IR004	20.0

Table 2.3. (con)

*FERTILIZERS

#F FDATE FMOD

1 93148 FE005
1 93194 FE0052 93148 FE005
2 93148 FE014
2 93194 FE0053 93148 FE005
3 93148 FE001
3 93194 FE0054 93148 FE005
4 93148 FE014
4 93194 FE0055 93148 FE005
5 93148 FE014
5 93194 FE0056 93148 FE001
6 93148 FE005
6 93194 FE0057 93148 FE001
7 93148 FE005
7 93194 FE005

*RESIDUES AND OTHERS

#R RDATE RMOD

1 93148 IB001

*SOIL ANALYSTS

#A SDATE SMOD

1 93118 -99

#A SDEL SADM

1 11.0 1.40

1 21.0 1.55

1 31.0 1.55

1 41.0 1.55

1 51.0 1.50

1 61.0 1.50

1 71.0 1.55

1 81.0 1.35

1 91.0 1.35

1 101.0 1.35

*HARVEST DETAILS

#H HDATE HSTG

1 93226 #9

*SIMULATION CONTROL

#N GENERAL

1 GE

#N OPTIONS

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#N METHODS

1 ME

#N MANAGEMENT

1 MA

#N OUTPUTS

1 OU

Table 2.3. (cont'd).

*FERTILIZERS (INORGANIC)

EF	FDATE	FMCD	FACD	FDEP	FAMN	FAMP
1	93148	FE005	AP004	4.0	40	
1	93184	FE005	AP004	4.0	40	
2	93148	FE005	AP004	4.0	40	
2	93148	FE014	AP002	4.0		22
2	93184	FE005	AP004	4.0	40	
3	93148	FE005	AP004	4.0	40	
3	93148	FE021	AP002	4.0		22
3	93184	FE005	AP004	4.0	40	
4	93148	FE005	AP004	4.0	40	
4	93148	FE014	AP002	4.0		44
4	93184	FE005	AP004	4.0	40	
5	93148	FE005	AP004	4.0	40	
5	93148	FE014	AP002	4.0		88
5	93184	FE005	AP002	4.0	40	
6	93148	FE021	AP002	4.0		88
6	93148	FE005	AP004	4.0	40	
6	93184	FE005	AP004	4.0	40	
7	93148	FE021	AP002	4.0		176
7	93148	FE005	AP004	4.0	40	
7	93184	FE005	AP004	4.0	40	

*RESIDUES AND OTHER ORGANIC MATERIALS

ER	RDATE	RCOD	RAMT	RESN	RESP	RESK	RINP	RDEP
1	93048	IB001	2000	-99	-99	-99	100.0	25.0

*SOIL ANALYSIS

EA	SADAT	SMOC	SMNI	SMHW	SMHB	SMPX	SMKE
1	93118	-99	IB001	SA009	-99	1B002	SA005

EA	SABL	SADM	SAOC	SANI	SAHW	SAHB	SAEX	SAKE
1	10.0	1.40	2.27	2.5	5.50	-99	4.33	0.60
1	20.0	1.55	2.27	2.5	5.50	-99	4.10	0.60
1	30.0	1.55	1.15	2.0	5.30	-99	3.57	0.29
1	40.0	1.55	1.64	2.0	5.30	-99	2.91	0.31
1	50.0	1.50	1.80	2.0	5.20	-99	2.02	0.27
1	60.0	1.50	1.80	1.5	5.40	-99	1.47	0.31
1	70.0	1.55	1.60	1.5	5.70	-99	2.05	0.29
1	80.0	1.35	1.60	1.5	5.50	-99	1.64	0.28
1	90.0	1.35	0.55	1.5	5.50	-99	1.71	0.26
1	100.0	1.35	0.55	1.5	5.50	-99	1.54	0.31

*HARVEST DETAILS

EL	HDATE	HSTG	HCOM	HSIZ	HPC
1	93226	R9	HL	LRG	100

*SIMULATION CONTROLS

EN	GENERAL	NYERS	NREPS	START	YRDAY	RSEED	SNAM					
1	GE	1	1	S	93121	2150	PHOSPH-BEAN 1993 IRRIGATED EXPERIMENT					
EN	OPTIONS	WATER	NITRO	SYMBI	PHOSP	POTAS	DISES					
1	OP	Y	Y	Y	Y	N	N					
EN	METHODS	WTHR	INCON	LIGHT	EVAPO	INFIL	PHOTO					
1	ME	M	M	E	R	S	C					
EN	MANAGEMENT	PLANT	IRRIG	FERTI	RESID	HARVS						
1	MA	R	R	R	R	M						
EN	OUTPUTS	FNAME	OVVEW	SUMRY	FROPT	GROTH	CARBN	WATER	NITRO	MINER	DISES	LONG
1	OU	N	Y	Y	1	Y	Y	Y	Y	Y	N	Y

Table 2.4. Exa

*WEATHER : M

9 INSI	LP
9000	-6.1
9001	15.7
9002	14.3
9003	11.6
9004	12.3
9005	16.1
9006	21.1
9007	27.7
9008	11.9
9009	16.2
9010	14.3
9011	14.3
9012	11.6
9013	9.8
9014	9.8
9015	8.8
9016	11.4
9017	18.8
9018	9.7
9019	15.3
9020	19.5
9021	9.0
9022	16.2
9023	15.5
9024	17.9
9025	17.4
9026	13.4
9027	17.6
9028	16.9
9029	20.4
9030	16.2
9031	17.0
9032	18.0
9033	13.2
9034	13.4
9035	16.0
9036	11.1
9037	11.8
9038	19.5
9039	18.6
9040	14.8
9041	19.8
9042	10.1
9043	18.6
9044	8.8
9045	10.2
9046	14.2
9047	11.9
9048	12.9
9049	20.8
9050	15.8
9051	15.4
9052	15.8
9053	17.1
9054	21.7
9055	13.3
9056	12.9
9057	12.9
9058	11.9
9059	14.7

Table 2.4. Example of the weather variables used to run bean model BEANGRO.

*WEATHER :MOROGORO TANZANIA

# INSI		LAT	LONG	ELEV
SUMO		-6.5	37.3	525
#DATE	SRAD	TMAX	TMIN	RAIN
93121	15.7	22.0	21.1	7.0
93122	14.3	30.2	21.1	5.0
93123	11.6	28.0	20.6	8.9
93124	12.3	30.0	21.0	0.6
93125	16.1	30.8	21.6	0.0
93126	21.1	31.1	19.9	0.0
93127	17.7	29.2	19.9	0.0
93128	11.9	29.0	21.2	24.4
93129	16.2	31.1	20.0	0.0
93130	14.3	30.3	21.0	26.5
93131	14.3	28.6	21.2	0.0
93132	11.8	26.4	18.4	0.0
93133	9.8	27.0	19.5	0.0
93134	9.8	26.2	20.2	0.5
93135	8.8	27.0	19.0	0.1
93136	11.4	29.0	17.0	0.0
93137	18.8	28.0	16.0	0.0
93138	9.7	27.5	15.6	0.0
93139	15.3	28.5	19.4	2.1
93140	19.5	25.7	19.7	2.7
93141	9.0	29.5	20.1	1.4
93142	16.2	28.0	19.2	7.5
93143	15.5	28.4	20.5	1.8
93144	17.9	30.4	19.9	0.0
93145	17.4	28.5	19.5	2.0
93146	13.4	30.1	19.0	0.0
93147	17.6	28.9	19.9	0.0
93148	16.9	30.0	17.5	0.0
93149	20.4	29.0	17.1	2.4
93150	16.2	30.0	19.5	4.4
93151	17.0	29.2	18.5	0.0
93152	18.2	28.5	16.8	0.0
93153	13.2	28.0	16.2	0.0
93154	13.4	28.5	17.0	0.0
93155	16.0	29.2	17.0	0.0
93156	11.1	25.5	16.3	0.0
93157	11.8	27.3	14.7	0.0
93158	19.5	28.4	14.5	0.0
93159	18.6	28.4	14.5	0.0
93160	14.8	27.4	14.6	1.0
93161	19.8	27.5	13.5	0.0
93162	10.1	24.8	13.5	0.0
93163	18.6	27.4	16.0	1.4
93164	8.8	26.2	14.0	0.0
93165	10.2	27.0	18.6	2.0
93166	14.2	27.2	16.1	0.0
93167	11.9	26.1	17.4	0.0
93168	12.9	26.8	16.0	0.0
93169	20.8	26.0	16.0	0.0
93170	15.8	26.5	17.1	0.0
93171	15.4	27.0	15.8	1.2
93172	15.8	28.5	16.1	0.0
93173	17.1	28.0	16.0	0.0
93174	21.7	29.0	17.5	0.0
93175	17.1	27.6	16.5	0.0
93176	13.3	26.5	13.5	0.0
93177	12.9	26.4	14.0	2.5
93178	12.9	25.5	18.0	5.6
93179	11.9	26.6	17.8	0.0
93180	14.7	26.6	17.3	0.0

Table 2.5. Estimated genetic coefficients for Canadian Wonder and other Andean type cultivars used to evaluate the bean model BEANGRO under Tanzanian conditions.

*DRYBEAN GENOTYPE COEFFICIENTS - CRGRO950 MODEL

SVAR#	VRNAME	EQ#	CRDL	PRCN	PM-FL	FL-SH	FL-SB	RD-PM	FL-LF	LPAX	SLAVR	SIZE	XFRT	WTUCD	SFMUR	SDNOV	PODUR
1		1			4	4	5	6	7	8	9	10	11	12	13	14	15

Table 2.5. Estimated genetic coefficients for Canadian Wonder and other Andean type cultivars used to evaluate the bean model BEANGRO under Tanzanian conditions.

***DRYBEAN GENOTYPE COEFFICIENTS - CRGRO950 MODEL**

VAR#	VRNAME.....	ECO#	CSDL	PPSEN	EM-FL	FL-SH	FL-SD	SD-PM	FL-LF	LFMAX	SLAVR	SIZLF	XERT	WTPSD	SFDUR	SDPDV	PODUR
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
IB0011	Isabella		ANDEET	12.17	0.000	26.0	3.0	10.0	22.00	12.00	1.00	295.133.0	1.00	0.350	15.0	3.50	7.0
IB0012	Manitou		ANDEET	12.17	0.000	28.0	3.0	8.0	23.00	9.00	1.00	295.133.0	1.00	0.550	15.0	3.50	7.0
IB0013	Redcloud		ANDEET	12.17	0.000	24.5	2.0	11.0	25.50	7.00	1.00	355.133.0	1.00	0.550	11.0	3.50	3.5
IB0014	Canadian Wonder+		ANDEET	12.17	0.000	24.0	2.0	7.5	22.00	7.00	1.00	355.133.0	1.00	0.550	13.0	3.50	3.5

! Definitions

! ECO# Code for the ecotype to which this cultivar belongs (see *.eco file)
 ! CSDL Critical Short Day Length below which reproductive development progresses with no daylength effect (hour)
 ! PPSEN Slope of the relative response of development to photoperiod with time (1/hour)
 ! EM-FL Time between plant emergence and flower appearance (R1) (photothermal days)
 ! FL-SH Time between first flower and first pod (R3) (photothermal days)
 ! FL-SD Time between first flower and first seed (R5) (photothermal days)
 ! SD-PM Time between first seed (R5) and physiological maturity (R7) (photothermal days)
 ! FL-LF Time between first flower (R1) and end of leaf expansion (photothermal days)
 ! LFMAX Maximum leaf photosynthesis rate at 30 C, 350 vpm CO₂, and high light (CO₂/m²-s)
 ! SLAVR Specific leaf area of cultivar under standard growth conditions (cm²/g)
 ! SIZLF Maximum size of full leaf (three leaflets) (cm²)
 ! XFRT Maximum fraction of daily growth that is partitioned to seed + shell
 ! WTPSD Maximum weight per seed (g)
 ! SFDUR Seed filling duration for pod cohort at standard growth conditions (photothermal days)
 ! SDPDV Average seed per pod under standard growing conditions (#/pod)
 ! PODUR Time required for cultivar to reach final pod load under optimal conditions (photothermal days)

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Cultivar Coefficients Calibration

Genetic coefficients in FILEC for the Canadian Wonder variety used in this study were calibrated using the methods suggested by Hoogenboom *et al.* (1991) and Boote (1994). Cultivar coefficient estimation steps involved initial simulations using the already available Canadian Wonder coefficients as defaults in the BEANGRO crop simulation model, followed by a trial and error approach to estimate the values.

The stepwise process involved in calibration of the genetic characteristics was to first estimate the crop life cycle by adjusting the EM-FL (i.e., minimum time³ between emergence (V_2) and flower appearance (R_1) growth stages in photothermal days), until the correct date of flowering was attained. The SD-PM (i.e., minimum time between R_5 and R_7 growth stages) was then adjusted until simulated and field measured dates of physiological maturity were approximately the same. The following step involved the estimation of dry matter accumulation at flowering, pod yield (kg ha^{-1}), seed yield (kg ha^{-1}), seed m^2 at maturity and the maximum LAI. This was done by adjusting EM-FL, FL-SH (i.e., time between plant first flower and first pod R_3 growth stage), FL-SD (i.e., time between first flower and first seed (R_3), FL-LF (i.e., minimum time between R_1 and R_5 growth stages). The SFDUR (i.e., time for seed filling period in a pod) and PODUR (i.e., time required for a cultivar to reach final pod load under optimum conditions) were also adjusted.

LAI was calibrated by manipulating SLAVR (i.e., specific leaf area under field conditions during the season, $\text{cm}^2 \text{g}^{-1}$) and the SIZLF (i.e., maximum size of three leaflets or

³Time in this context refers to photothermal time as defined by Jones *et al.* (1991).

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trifoliolates, cm^2). Calibration for seed size, seeds per pod was done by making necessary changes in WTPSD (maximum weight seed g^{-1} under nonlimiting field conditions).

Some species parameters in the species file (SPE) were adjusted using field measured values. These parameters included plant P values for maximum concentration (%) in roots (PPRTMX), stems (PPSTMX), leaves (PPLFMX), seeds (PPSDM), and in shells (PPSHMX). The minimum values for the same plant parts were also adjusted using measured values. Leaf parameters such as maximum (SLAMAX), and minimum (SLAMIN) and specific leaf area (SLA) were also adjusted using field measured values. Biomass accumulation during the vegetative and reproductive growth phases were matched by adjusting parameters CMOBMX (i.e., proportion CH_2O reserves that can be mobilized in a day) and CADSTF (i.e., CH_2O added to stem reserves at the end of day after growth $\text{g}[\text{CH}_2\text{O}] \text{m}^2 \text{d}^{-1}$). To match the simulated pod yield, seed yield, and seed number (m^{-2}) with those measured under field conditions, the maximum threshing percentage (THRSH) was set at 63% in the ecotype (ECO) file.

The above steps were repeated until reasonable agreements between simulated and field measured values of anthesis and physiological maturity dates, maximum LAI, pod yield (kg ha^{-1}), seed yield (kg ha^{-1}), and seed m^2 , seed size (g seed^{-1}) at harvest maturity were obtained under optimum field conditions. The genetic coefficients obtained were used to simulate other treatments. Since the same bean cultivar was used in both years of study, the genetic coefficients generated during the calibration process were tested against data from the other experiment of the 1993 season, and the experiments of the 1994 season. The equations and parameters governing the main processes for the P in the P-submodel for both the TSP and MPR fertilizers used in this study are described in Chapter 3.

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Model Evaluation

The model was tested by comparing simulated values with field collected data. Comparisons of growth, development, and yield variables obtained from field trials with variables the model predicted under identical conditions were made for rainfed, and irrigated experiments for the 1993 and the 1994 growing seasons.

The model was evaluated under P limiting and nonlimiting conditions. This was done by switching on or switching off the P simulation process using the option provided in the simulation control section in the input file.

Each experiment was simulated separately. Since applied N to the experiment was a non-experimental variable in both experiments, it was not used for model evaluation.

RESULTS AND DISCUSSION

Soil Profiles Properties

Values for the soil properties used in the model are given in Tables 2 a and 2b. The drained upper limit for the irrigated site (Alfisol, isohyperthermic, typic tropustic) was between 0.192 to 0.265 cm cm⁻³. For the rainfed site (Oxisol, isohyperthermic, aridic tropustic) it was between 0.189 to 0.301 cm³ cm⁻³. The total profile depth at each site was 100 cm. The watertable was 85 cm at the irrigated site, and below 110 cm at the rainfed site during the rainy periods. Both soil profiles had high bulk densities ranging from 1.35 to 1.55 g cm⁻³ at the irrigated site, and 1.29 to 1.65 g cm⁻³ at the rainfed site. The native soil K reserves were low. This may have been due to clay minerals at both sites being predominantly kaolinitic,

which are pooled
the top layer of
water entry and
content during
shown in Appendix

Monthly
season, and April
mid-May to mid-
periods averaged
 $14.75 \text{ MJ m}^{-2} \text{ d}^{-1}$
experiments re-
(Figure 2.2). In
the 1993 season
growth stage.
second crop was
for replanting
during the di-
came in the form
as runoff (Figure

which are poor in K (Thung, 1991). Before the onset of rain, some cracks were observed in the top layer of the soil profile at the irrigated site. Such condition may have influenced the water entry and redistribution in the soil during the first days of the rain. Soil profile water content during the experimental periods were not measured. Soil profile descriptions are shown in Appendix 1a for the rainfed site and Appendix 1b for the irrigated site.

Weather During the Study

Monthly mean values for the weather variables are shown in Appendix 2a for the 1993 season, and Appendix 2b for the 1994 season. Daily temperature patterns were lower from mid-May to mid July in both seasons (Figure 2.1). Solar radiation during the experimental periods averaged 14.70 MJ m^{-2} in 1993, and 14.06 MJ m^{-2} in 1994 in the rainfed plots, and 14.75 MJ m^{-2} in 1993, and 15.14 MJ m^{-2} in 1994 in the irrigated plots. In general terms, both experiments received the same amount of solar radiation in the 1993 and 1994 seasons (Figure 2.2). Due to the intense and long thunderstorms, the irrigated site was flooded during the 1993 season when the treatments had already been applied, and the crop was at the R_1 growth stage. Consequently, the first crop sown on May 8 had to be replanted later. The second crop was sown at the same site on May 28, 1993 after the plots were dry and ready for replanting. The rainfed experiments differed markedly in the amount of rainfall received during the different growth phases. Much of the rainfall received during the rainy seasons came in the form of intense thunderstorms, resulting in a higher percentage of water being lost as runoff (Figure 2.3). Due to the delay of the onset of rains during the 1994 season, planting

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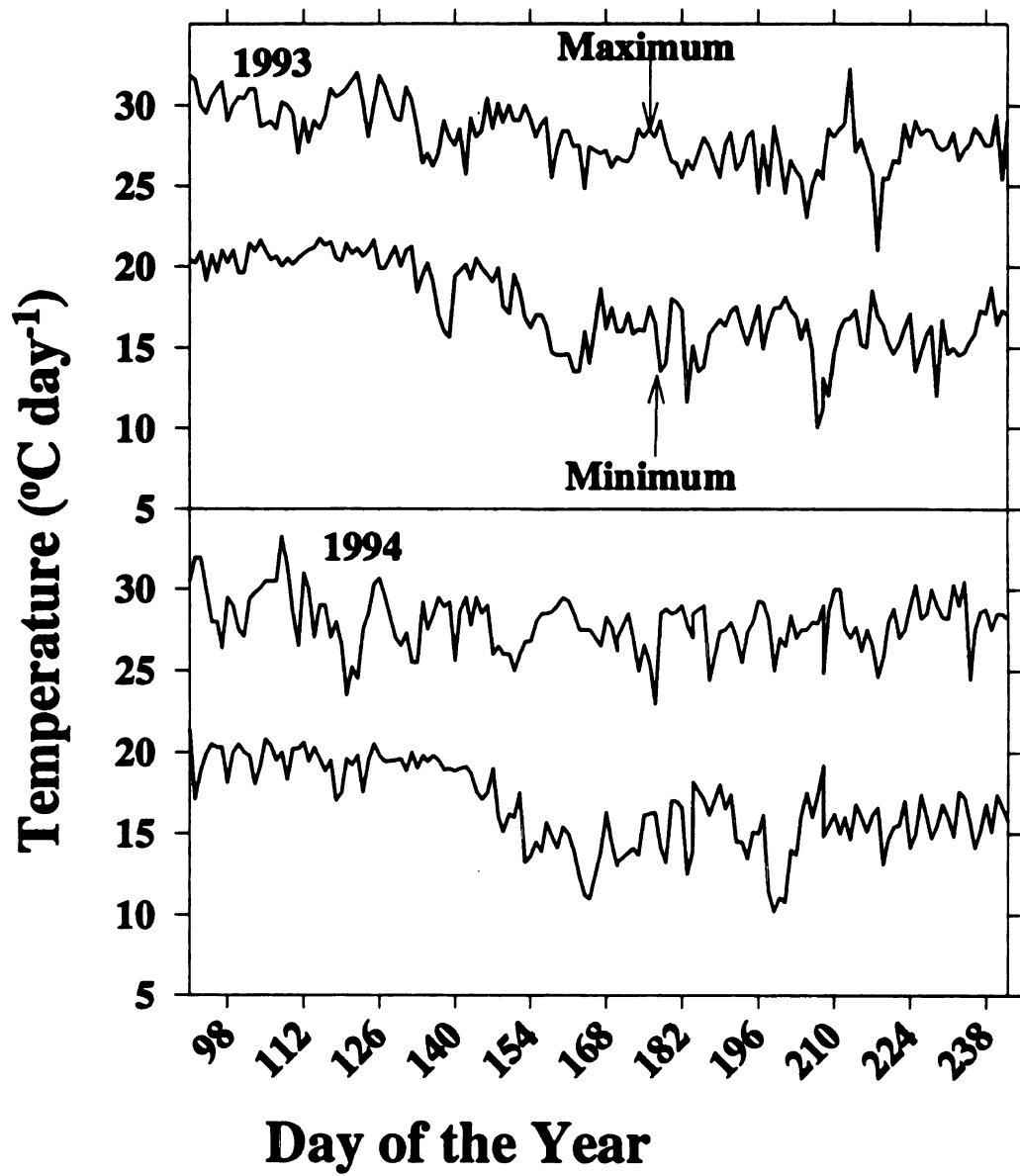
loss due to th

was also delayed by 10 days compared to the 1993 season planting date of the rainfed experiment.

Common diseases included rust (*Uromyces appendiculatus*), angular leaf spot (*Mycosphaerella pinodes*), and white mold (*Sclerotinia sclerotiorum*). At harvest, seeds were attacked by ascochyta blight (*Ascochyta* spp) which resulted in yield losses, and reduced seed quality. The disease was more serious in the experiment grown during the relatively cool periods (May-August) when water (from irrigation) and high humidity were abundant. Seed loss due to this disease was as high as 20% in some plots.

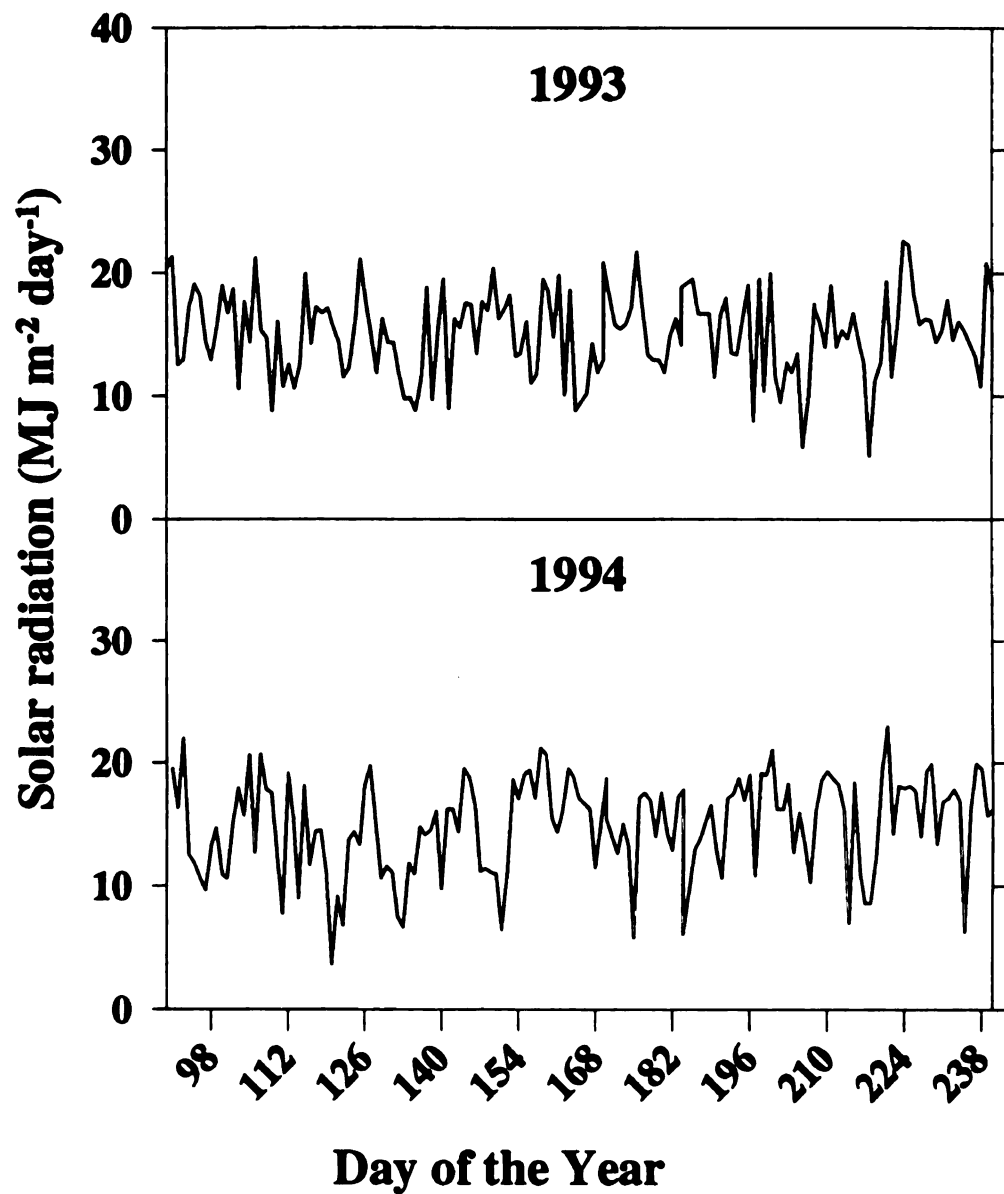
Temperature (°C)

Figure 2.1. Sea
seasons.



Planting day of the Year:
094 Rainfed 1993
104 Rainfed 1994
148 Irrigated 1993
128 Irrigated 1994

Figure 2.1. Seasonal patterns of temperature regimes during the 1993 and 1994 growing seasons.



Planting day of the Year:

094 Rainfed 1993

104 Rainfed 1994

148 Irrigated 1993

128 Irrigated 1994

Figure 2.2. Seasonal patterns of solar radiation during the 1993 and 1994 growing seasons.

Figure 2.3. Se
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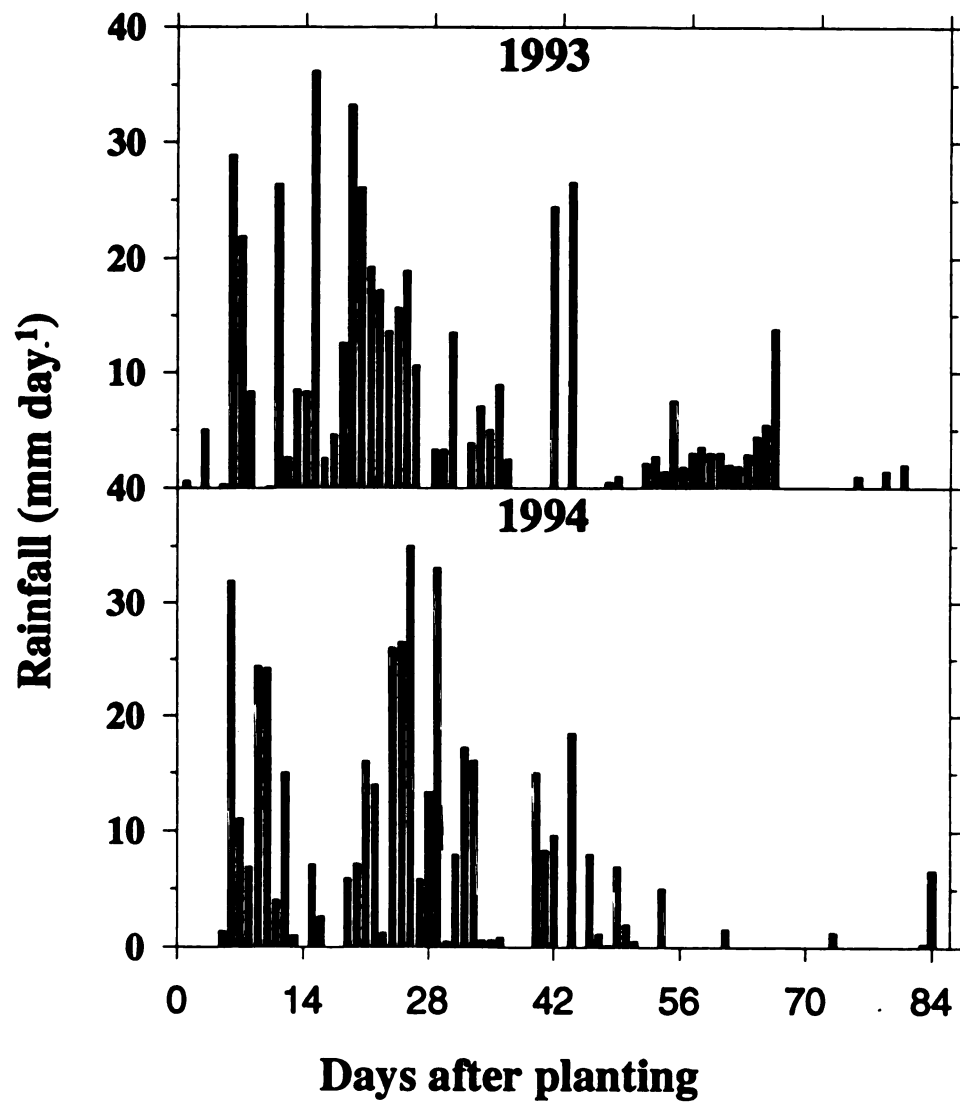


Figure 2.3. Seasonal patterns of rainfall distribution during the 1993 and 1994 growing seasons.

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Cultivar Genetic Coefficients

Table 2.5 shows the genetic coefficients of Canadian Wonder cultivar used to calibrate the bean model against the data obtained from the 1993 irrigated experiment, with 88 kg P ha⁻¹ (TSP) treatment. To get the best results on BEANGRO model performance, this study showed that calibration should start by predicting life cycle timing, then calibrate traits to predict seed filling duration, average seeds per pod, time to reach final pod load, pod and seed yield, seed size, and finally, fine tune total dry matter accumulation at harvest maturity. The maximum THRSH (shelling percentage) in the ECO file was found to be an important trait to be considered during the calibration process.

Field Measured Results

Model performance for predicting P concentration (%) and total P uptake (kg ha⁻¹) at various growth stages, and grain P (kg ha⁻¹) at maturity as compared to field measured values are discussed in Chapter 3. Field measured total dry matter, yield components and response of bean to different forms and amounts of applied fertilizer P are discussed in detail in Chapters 4 and 5.

Rainfall amount at the location, 523 mm during 1993 and 342 mm during 1994 growing seasons, was poorly distributed, especially during the 1994 season, creating unfavorable conditions for good crop performance during the reproductive growth stage for the rainfed experiment (Figure 2.3). Low temperatures from June to August (Appendices 2a

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and 2b) when the irrigated experiments were conducted, slightly delayed vegetative and reproductive developments compared to the rainfed experiments.

Plant population (plants m^{-2}) count taken at the V_3 growth stage showed that seed germination, crop vigor and emergence were very good. However, plant population decreased at maturity regardless of the fertilizer treatments (Appendices 5a and 5b) in both experiments. Therefore, plant population in this study was considered suboptimal at harvest maturity in most plots. Growth, development, yield, and yield components data collected during the study from each experiment formed an independent data set used to evaluate the model performance.

Model Evaluation Results

The second objective of this study was to evaluate the ability of the BEANGRO model to simulate bean growth, development, yield, and seed yield components. Once the genetic coefficients in the cultivar file and crop constants in the species, and ecotype files were estimated (see Materials and Methods), they were fixed so the accuracy of the model could be determined against field measured data.

Under the 1993 irrigated, and nonlimiting P conditions (i.e., P switched off), the model correctly predicted the dates for anthesis, timing of the pod and seed set, seed size (mg seed^{-1}) and seeds pod^{-1} . Simulated pod yield (kg ha^{-1}), and seed yield (kg ha^{-1}) at harvest maturity were over predicted compared to the results measured under field conditions (Table 2.6 a). The model under predicted the crop performance in terms of biomass accumulation (kg ha^{-1}) by 4%. The under prediction of biomass accumulation with nonlimiting P conditions

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were due to the high persisting senescence process after R₇ growth stage. Such condition could be due to the high demand of N during the pod filling phase (Sinclair and de Wit, 1976), or due to the source-sink relationship (White and Izquierdo, 1991).

Under the rainfed, and nonlimiting P conditions the anthesis date was over predicted by two days, while the physiological maturity was accurately predicted. However, the model under predicted total biomass accumulation by 13% at anthesis, and over predicted it by 3% at harvest maturity (Table 2.6 b). The results from the 1994 season were similar to those of the 1993 season except that the model over predicted the biomass production by 54% under irrigated conditions, and under predicted its accumulation by 16% under rainfed conditions. The simulation results showed water stress factor of 0.26 at pod formation to 0.75 at physiological maturity. Such a condition may have influenced the low predicted biomass accumulation observed under the 1994 rainfed conditions.

Application of P fertilizer under irrigation conditions did not affect the timing of the crop growth stages. The model accurately predicted the vegetative, reproductive developments and physiological maturity with the 0 kg P ha⁻¹ treatment under irrigation conditions of the 1993 season. However, seed yield, seed number (m⁻²) seed size, maximum LAI, and biomass accumulation at anthesis were all under predicted by the model. The biomass accumulation at harvest maturity was over predicted by 20% by the model at harvest maturity (Table 2.7 a). Under the rainfed experiment, flowering stage was over predicted by three days. The results on seed yield components were as reported under irrigated conditions, except that seed m⁻² was under predicted by 44% while seed pod⁻¹ were over predicted by 11%. Biomass at harvest maturity was over predicted by 26% (Table 2.7 b).

Table 2.6. 4
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(a) The irriga

*MAIN GROWTH

1	VARIABLE

	ANTHESIS
	FIRST F
	FIRST S
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	POD YIEL
	SEED YI
	SHELLIN
	WEIGHT
	SEED NO
	SEEDS P
	MAXIMUM
	BIOMASS
	BIOMASS
	HARVEST

(b) The rainfe

*MAIN GROWTH A

1	VARIABLE

	ANTHESIS
	FIRST PO
	FIRST SE
	PHYSIOLO
	POD YIEL
	SEED YIEL
	SHELLING
	WEIGHT P
	SEED NO
	SEEDS P
	MAXIMUM
	BIOMASS
	BIOMASS
	HARVEST

¹ TSP refers to tr

Table 2.6. Summary of simulation outputs of bean performance under nonlimiting P conditions (P switched off) compared with the high P rate for the 1993 season.

(a) The irrigated experiment.

*MAIN GROWTH AND DEVELOPMENT VARIABLES		TSP	
e	VARIABLE	PREDICTED	MEASURED
	-----	-----	-----
	ANTHESIS DATE (dap)	31	32
	FIRST POD (dap)	34	36
	FIRST SEED (dap)	40	41
	PHYSIOLOGICAL MATURITY (dap)	66	66
	POD YIELD (kg/ha)	2079	1488
	SEED YIELD (kg/ha)	1508	1215
	SHELLING PERCENTAGE (%)	72.53	81.65
	WEIGHT PER SEED (g)	.392	.314
	SEED NUMBER (SEED/m ²)	384	387
	SEEDS/POD	3.50	3.47
	MAXIMUM LAI (m ² /m ²)	3.04	3.00
	BIOMASS (kg/ha) AT ANTHESIS	1240	1298
	BIOMASS (kg/ha) AT HARVEST MAT.	3997	4160
	HARVEST INDEX (kg/kg)	.377	.292

(b) The rainfed experiment.

*MAIN GROWTH AND DEVELOPMENT VARIABLES		TSP	
e	VARIABLE	PREDICTED	MEASURED
	-----	-----	-----
	ANTHESIS DATE (dap)	31	29
	FIRST POD (dap)	33	32
	FIRST SEED (dap)	38	33
	PHYSIOLOGICAL MATURITY (dap)	60	60
	POD YIELD (kg/ha)	1452	1714
	SEED YIELD (kg/ha)	1054	1037
	SHELLING PERCENTAGE (%)	72.60	60.5
	WEIGHT PER SEED (g)	.352	.270
	SEED NUMBER (SEED/m ²)	300	340
	SEEDS/POD	3.50	3.70
	MAXIMUM LAI (m ² /m ²)	2.44	2.20
	BIOMASS (kg/ha) AT ANTHESIS	946	1096
	BIOMASS (kg/ha) AT HARVEST MAT.	2734	2658
	HARVEST INDEX (kg/kg)	.386	.390

¹ TSP refers to triple superphosphate fertilizer

Table 2.7. Su
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(a) The irrig

*MAIN GROWTH

#	VARIABLE
1	ANTHESIS
2	FIRST FL
3	FIRST SE
4	PHYSIOLOG
5	POD YIELD
6	SEED YIELD
7	SHELLING
8	WEIGHT
9	SEED NUM
10	SEEDS/PO
11	MAXIMUM
12	BIOMASS
13	BIOMASS
14	HARVEST

(b) The rainfed

*MAIN GROWTH

#	VARIABLE
1	ANTHESIS
2	FIRST FL
3	FIRST SE
4	PHYSIOLOG
5	POD YIELD
6	SEED YIELD
7	SHELLING
8	WEIGHT
9	SEED NUM
10	SEEDS/PO
11	MAXIMUM
12	BIOMASS
13	BIOMASS
14	HARVEST

Table 2.7. Summary of simulation outputs of bean performance under control conditions (0 kg P ha⁻¹) for the 1993 season.

(a) The irrigated experiment.

***MAIN GROWTH AND DEVELOPMENT VARIABLES**

e	VARIABLE	PREDICTED	MEASURED
	-----	-----	-----
	ANTHESIS DATE (dap)	31	32
	FIRST POD (dap)	34	36
	FIRST SEED (dap)	40	41
	PHYSIOLOGICAL MATURITY (dap)	66	66
	POD YIELD (kg/ha)	393	496
	SEED YIELD (kg/ha)	281	329
	SHELLING PERCENTAGE (%)	71.66	66.33
	WEIGHT PER SEED (g)	.310	.330
	SEED NUMBER (SEED/m ²)	91	100
	SEEDS/POD	3.50	3.50
	MAXIMUM LAI (m ² /m ²)	0.99	1.74
	BIOMASS (kg/ha) AT ANTHESIS	732	947
	BIOMASS (kg/ha) AT HARVEST MAT.	1412	1129
	HARVEST INDEX (kg/kg)	.199	.291

(b) The rainfed experiment.

***MAIN GROWTH AND DEVELOPMENT VARIABLES**

e	VARIABLE	PREDICTED	MEASURED
	-----	-----	-----
	ANTHESIS DATE (dap)	31	28
	FIRST POD (dap)	33	30
	FIRST SEED (dap)	38	32
	PHYSIOLOGICAL MATURITY (dap)	63	63
	POD YIELD (kg/ha)	411	444
	SEED YIELD (kg/ha)	296	271
	SHELLING PERCENTAGE (%)	72.01	61.1
	WEIGHT PER SEED (g)	.473	.252
	SEED NUMBER (SEED/m ²)	63	107
	SEEDS/POD	3.50	3.13
	MAXIMUM LAI (m ² /m ²)	0.90	1.42
	BIOMASS (kg/ha) AT ANTHESIS	633	726
	BIOMASS (kg/ha) AT HARVEST MAT.	1285	956
	HARVEST INDEX (kg/kg)	.230	.284

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Biomass accumulation predicted by the model at harvest maturity was high compared to that measured from the field applied with 22 kg P ha⁻¹ in form of TSP and low with MPR fertilizers under irrigated conditions (Table 2.8 a). With TSP application, seeds pod⁻¹, maximum LAI, and biomass accumulation at anthesis were accurately predicted. Under rainfed conditions, biomass accumulation at anthesis agreed well with the values measured from the field, while that at physiological maturity was over predicted by 27% with application of TSP. Similar results were obtained by the application of MPR at the same rate except that at harvest maturity, biomass model prediction was higher than that measured from the field by 47% (Table 2.8b).

The simulation results further showed that medium P rate (44 kg P ha⁻¹ TSP) used in the simulations over predicted the crop performance in terms of biomass accumulation at anthesis and physiological maturity (Tables 2.9 a). The model predicted seed value was closer to field measured data under rainfed conditions of the 1993 season than that from the irrigated conditions at 44 kg P ha⁻¹ (Table 2.9 b). Overall, the results show that apart from the discrepancy in the prediction of biomass accumulation at harvest maturity, the model correctly predicted the bean yield with application of different P fertilizer types and levels.

Table 2.8. Summary of simulation outputs of bean performance under low P rate conditions (22 kg P ha⁻¹) for the 1993 season.

(a) The irrigated experiment.

*MAIN GROWTH AND DEVELOPMENT VARIABLES		TSP ¹		MPR ²	
e	VARIABLE	PREDICTED	MEASURED	PREDICTED	M E A S U R E D
	-----	-----	-----	-----	-----
	ANTHESIS DATE (dap)	31	32	31	32
	FIRST POD (dap)	34	36	34	36
	FIRST SEED (dap)	40	41	40	41
	PHYSIOLOGICAL MATURITY (dap)	66	66	66	66
	POD YIELD (kg/ha)	795	891	1086	812
	SEED YIELD (kg/ha)	576	604	784	570
	SHELLING PERCENTAGE (%)	72.47	67.79	72.15	70.20
	WEIGHT PER SEED (g)	.368	.332	.410	.287
	SEED NUMBER (SEED/m ²)	158	182	191	199
	SEEDS/POD	3.50	3.60	3.50	3.37
	MAXIMUM LAI (m ² /m ²)	1.93	1.76	1.69	1.97
	BIOMASS (kg/ha) AT ANTHESIS	1168	1035	1040	1197
	BIOMASS (kg/ha) AT HARVEST MAT.	3144	2955	2686	2888
	HARVEST INDEX (kg/kg)	.183	.204	.292	.197

(b) The rainfed experiment.

*MAIN GROWTH AND DEVELOPMENT VARIABLES		TSP		MPR	
e	VARIABLE	PREDICTED	MEASURED	PREDICTED	M E A S U R E D
	-----	-----	-----	-----	-----
	ANTHESIS DATE (dap)	31	28	31	28
	FIRST POD (dap)	33	30	33	30
	FIRST SEED (dap)	38	32	38	32
	PHYSIOLOGICAL MATURITY (dap)	62	63	62	63
	POD YIELD (kg/ha)	908	812	964	621
	SEED YIELD (kg/ha)	654	508	698	386
	SHELLING PERCENTAGE (%)	72.07	62.6	72.3	62.1
	WEIGHT PER SEED (g)	.470	.274	.480	.270
	SEED NUMBER (SEED/m ²)	139	186	145	144
	SEEDS/POD	3.50	3.33	3.50	3.73
	MAXIMUM LAI (m ² /m ²)	1.94	1.61	1.65	2.33
	BIOMASS (kg/ha) AT ANTHESIS	933	969	894	803
	BIOMASS (kg/ha) AT HARVEST MAT.	2422	1756	2211	1155
	HARVEST INDEX (kg/kg)	.270	.289	.316	.334

¹ TSP refers to triple superphosphate fertilizer

² MPR refers to Minjingu phosphate rock fertilizer

Table 2.9.
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(a) The irrig

*MAIN GROWTH

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(b) The rainf

*MAIN GROWTH

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HARVEST

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Table 2.9. Summary of simulation outputs of bean performance under medium P rate conditions (44 kg P ha⁻¹) for the 1993 season.

(a) The irrigated experiment.

*MAIN GROWTH AND DEVELOPMENT VARIABLES		TSP ¹	
e	VARIABLE	PREDICTED	MEASURED
	-----	-----	-----
	ANTHESIS DATE (dap)	31	32
	FIRST POD (dap)	34	36
	FIRST SEED (dap)	40	41
	PHYSIOLOGICAL MATURITY (dap)	66	66
	POD YIELD (kg/ha)	1293	1263
	SEED YIELD (kg/ha)	936	1030
	SHELLING PERCENTAGE (%)	72.3	81.6
	WEIGHT PER SEED (g)	.424	.330
	SEED NUMBER (SEED/m ²)	221	312
	SEEDS/POD	3.50	3.67
	MAXIMUM LAI (m ² /m ²)	2.36	2.68
	BIOMASS (kg/ha) AT ANTHESIS	1231	1121
	BIOMASS (kg/ha) AT HARVEST MAT.	3712	3518
	HARVEST INDEX (kg/kg)	.252	.293

(b) The rainfed experiment.

*MAIN GROWTH AND DEVELOPMENT VARIABLES		TSP	
e	VARIABLE	PREDICTED	MEASURED
	-----	-----	-----
	ANTHESIS DATE (dap)	33	29
	FIRST POD (dap)	34	32
	FIRST SEED (dap)	38	32
	PHYSIOLOGICAL MATURITY (dap)	62	63
	POD YIELD (kg/ha)	1190	1377
	SEED YIELD (kg/ha)	860	922
	SHELLING PERCENTAGE (%)	72.25	66.9
	WEIGHT PER SEED (g)	.470	.267
	SEED NUMBER (SEED/m ²)	183	341
	SEEDS/POD	3.50	4.03
	MAXIMUM LAI (m ² /m ²)	2.27	2.28
	BIOMASS (kg/ha) AT ANTHESIS	938	1030
	BIOMASS (kg/ha) AT HARVEST MAT.	2666	2472
	HARVEST INDEX (kg/kg)	.323	.373

¹TSP refers to triple superphosphate fertilizer

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Table 2.10 indicates the model predicted bean performance compared to the field measured values at equal fertilizer rates of TSP and MPR. The results show that the model predicted values agree well with the field measured values for the seed yield and biomass accumulation at physiological maturity. The differences were within the measured standard error values of the mean. Tables 2.6 to 2.10 also show comparisons between simulated (model predicted), and field measured maximum LAI. The LAI increased with crop growth at all P fertilizer levels. Overall, the predicted and field measured LAI values were maximum at R₅ growth stage. The field measured LAI values ranged from 1.75 in the 1993 season for the control rainfed conditions to 3.00 during the 1993 season for the 88 kg P ha⁻¹ irrigated conditions. Under nonlimiting P conditions, the simulated maximum LAI was over predicted by only 1% for irrigated experiment, and by 8 % for the rainfed experiment.

Results of reduction in LAI due to low P reported in this study from simulated and field measured values has also been reported by Adu-Gyamfi *et al.* (1990) in pigeon peas, and Yan *et al.* (1995a) in beans. The low field measured LAI values compared to predicted values reported here may also have been attributed to pest and disease infestation during the growing season. The predicted values in all treatments were within the standard error values associated with observed data.

Table 2.10.
(88 kg P ha⁻¹)

(a) The irrig

*MAIN GROWTH

8 VARIABLE

ANTHESIS
FIRST
FIRST
PHYSIOLOGICAL
POD YIELD
SEED YIELD
SHELLING
WEIGHT
SEED NUMBER
SEEDS PER
MAXIMUM
BIOMASS
BIOMASS
HARVEST

(b) The rainfed

*MAIN GROWTH

8 VARIABLE

ANTHESIS
FIRST
FIRST
PHYSIOLOGICAL
POD YIELD
SEED YIELD
SHELLING
WEIGHT
SEED NUMBER
SEEDS PER
MAXIMUM
BIOMASS
BIOMASS
HARVEST

¹ TSP = Triple super phosphate
² MPR = Muriatic phosphate

Table 2.10. Summary of simulation outputs of bean performance under high P rate conditions (88 kg P ha⁻¹ TSP) and medium P rate (88 kg P ha⁻¹ MPR) for the 1993 season.

(a) The irrigated experiment.

*MAIN GROWTH AND DEVELOPMENT VARIABLES		TSP ¹		MPR ²	
②	VARIABLE	PREDICTED	MEASURED	PREDICTED	M E A S U R E D
	-----	-----	-----	-----	-----
	ANTHESIS DATE (dap)	31	32	31	32
	FIRST POD (dap)	34	36	34	36
	FIRST SEED (dap)	40	41	40	41
	PHYSIOLOGICAL MATURITY (dap)	66	66	66	66
	POD YIELD (kg/ha)	1800	1488	1275	1222
	SEED YIELD (kg/ha)	1304	1215	921	967
	SHELLING PERCENTAGE (%)	72.41	81.65	72.25	79.13
	WEIGHT PER SEED (g)	.420	.314	.410	.298
	SEED NUMBER (SEED/m ²)	310	387	225	324
	SEEDS/POD	3.50	3.47	3.50	3.70
	MAXIMUM LAI (m ² /m ²)	2.68	3.00	1.89	2.67
	BIOMASS (kg/ha) AT ANTHESIS	1229	1298	1111	1195
	BIOMASS (kg/ha) AT HARVEST MAT.	4006	4160	3056	2459
	HARVEST INDEX (kg/kg)	.325	.292	.306	.393

(b) The rainfed experiment.

*MAIN GROWTH AND DEVELOPMENT VARIABLES		TSP		MPR	
②	VARIABLE	PREDICTED	MEASURED	PREDICTED	M E A S U R E D
	-----	-----	-----	-----	-----
	ANTHESIS DATE (dap)	31	29	31	29
	FIRST POD (dap)	33	32	33	32
	FIRST SEED (dap)	38	33	38	33
	PHYSIOLOGICAL MATURITY (dap)	63	63	62	63
	POD YIELD (kg/ha)	1298	1714	1038	1378
	SEED YIELD (kg/ha)	942	1037	752	828
	SHELLING PERCENTAGE (%)	72.57	60.5	72.4	60.0
	WEIGHT PER SEED (g)	.393	.270	.473	.266
	SEED NUMBER (SEED/m ²)	239	340	159	311
	SEEDS/POD	3.50	3.70	3.50	4.30
	MAXIMUM LAI (m ² /m ²)	2.39	2.20	1.78	2.12
	BIOMASS (kg/ha) AT ANTHESIS	946	1096	917	1116
	BIOMASS (kg/ha) AT HARVEST MAT.	2785	2658	2338	2013
	HARVEST INDEX (kg/kg)	.338	.390	.322	.411

¹ TSP = Triple superphosphate

² MPR = Minjingu phosphate rock

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There was rapid decline of LAI at R_5 growth stage which coincided with the increase in pod weight starting at R_5 to R_7 growth stages. Fredeen *et al.* (1989) and Rao and Terry (1989) concluded that low P levels decrease growth primarily through the effect of leaf epidermal cell expansion rather than on rate of photosynthetic activity per unit area, as suggested by Whiteaker *et al.* (1976) and Le Bot *et al.* (1994). The decline in LAI with age shown by simulated and field measured values was due to senescence, death, and abscission of the leaves at a faster rate than new leaves were being formed. Furthermore, the period between R_6 and R_8 growth stages was for rapid grain filling process, therefore, the photosynthate and metabolites were being trans-located to the developing seeds.

Measured values for specific leaf area (SLA) ranged from 250 to 350 cm² g⁻¹ at flowering. The SLA values started slow, increased to maximum at R_5 growth stage, then declined toward maturity. The predicted SLA was about 20% higher than the field measured value. Differences between predicted and field measured SLA values may indicate how different P levels, pests and diseases affected the crop in the field.

Figures 2.4 a, b, c, and d show the simulated and field measured bean grain yield (kg ha⁻¹). Significant differences were observed among treatments in the grain production for the two experiments in both seasons. The model predicted grain yield formation with similar accuracy in various treatments (data not shown). The simulated grain yield ranged from 296 kg ha⁻¹ with the control treatment from the 1994 rainfed experiment to 1304 kg ha⁻¹ with kg P ha⁻¹ (TSP) treatment from the 1993 irrigated experiment.

The model predicted and field measured seed production increased as the levels of fertilizer P applied increased. This pattern was more visible in plots that received P in the form of TSP fertilizer (Figure 2.4a and b). However, in plots that received P in the form of

Grain yield (kg ha⁻¹)

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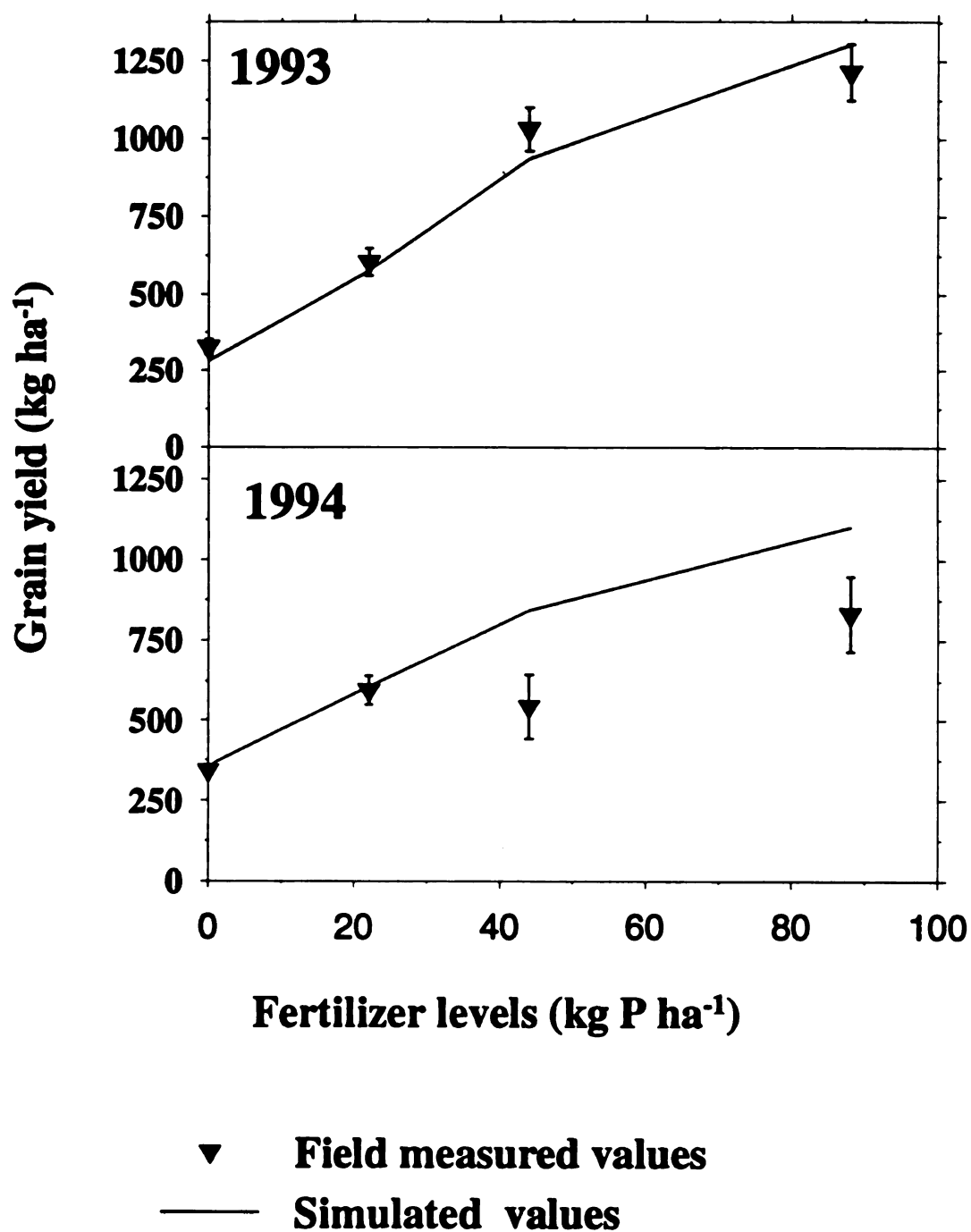


Figure 2.4a. Simulated and field measured grain yield with the application of TSP under irrigated conditions. Vertical bars represent standard errors of the mean.

Grain yield (kg ha⁻¹)

Figure 2.4
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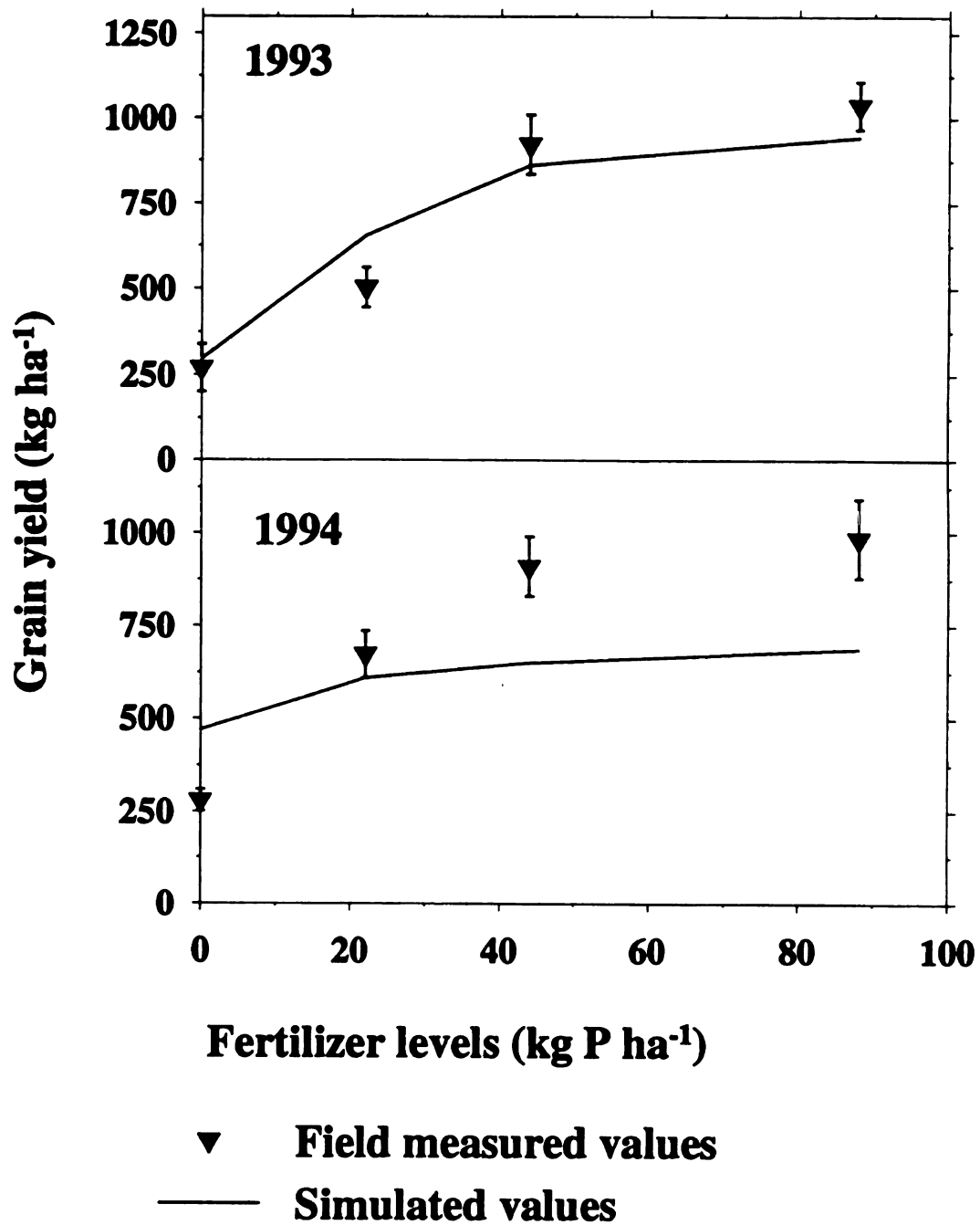


Figure 2.4b. Simulated and field measured grain yield with the application of TSP under rainfed conditions. Vertical bars represent standard errors of the mean.

Grain yield (kg ha⁻¹)

Figure 2.4c
under irriga

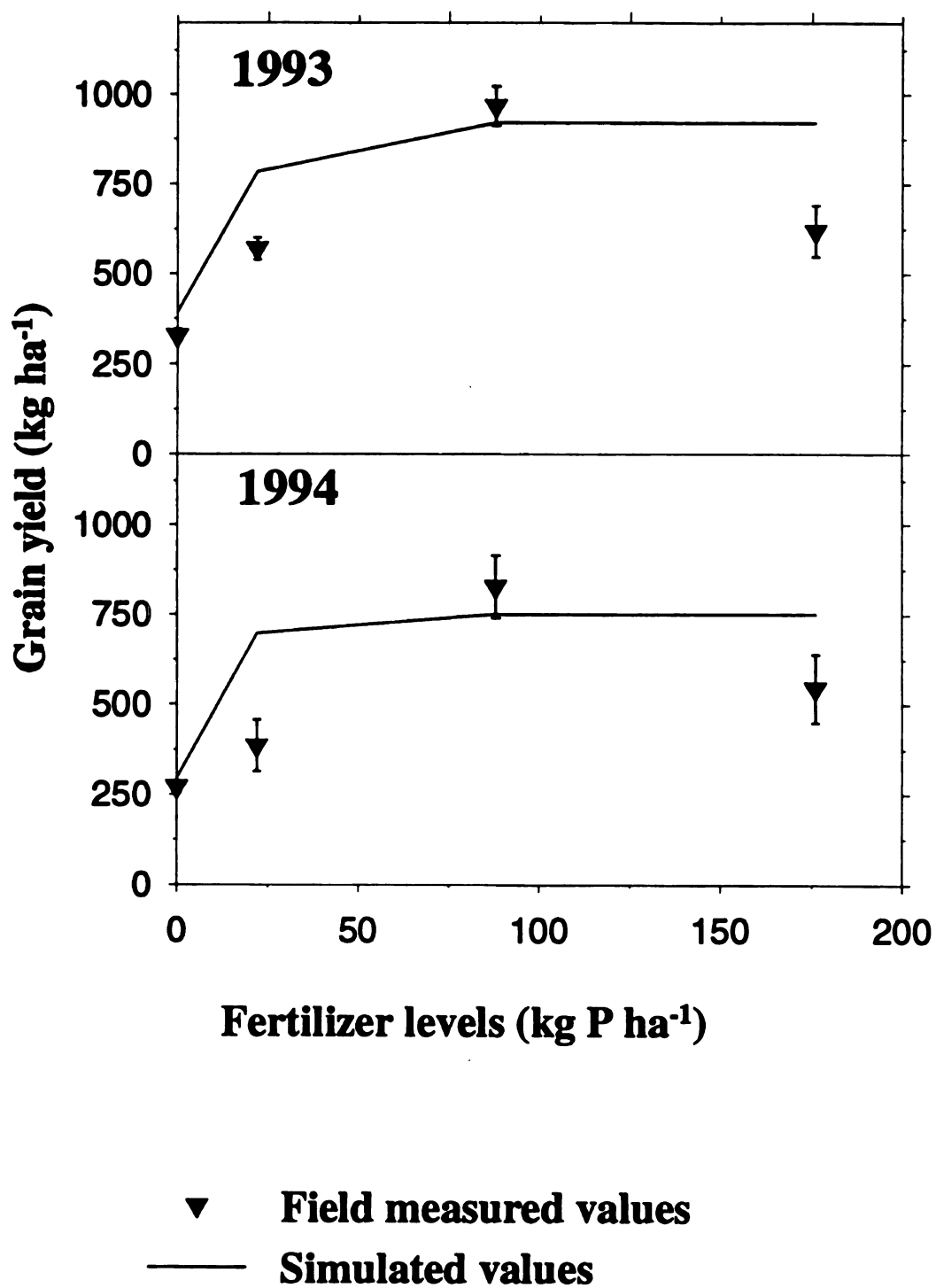


Figure 2.4c. Simulated and field measured grain yield with the application of MPR fertilizer under irrigated conditions. Vertical bars represent standard errors of the mean.

Grain yield (kg ha⁻¹)

Figure 2.4:
under rain

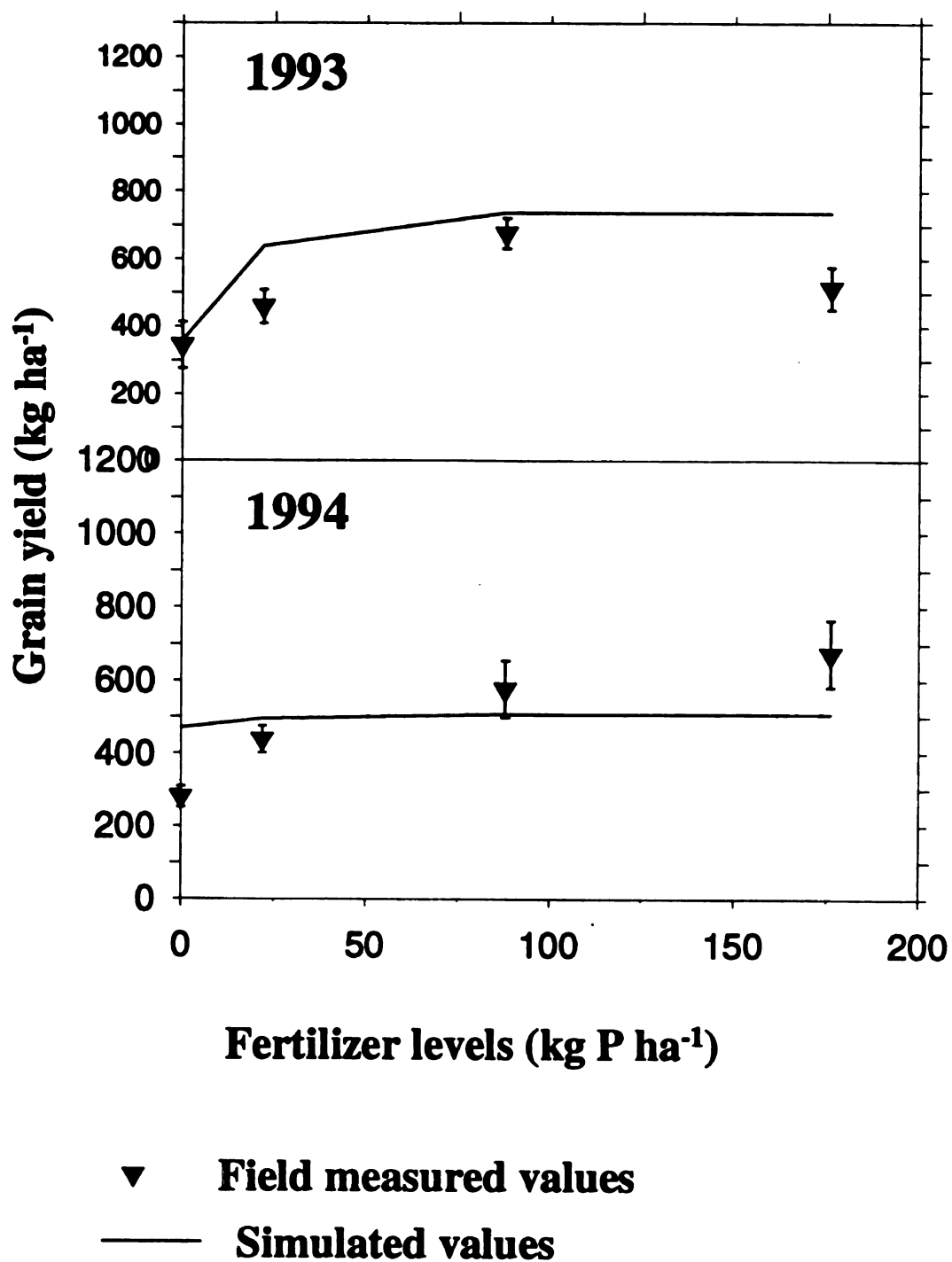


Figure 2.4d. Simulated and field measured grain yield with the application of MPR fertilizer under rainfed conditions. Vertical bars represent standard errors of the mean.

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MPR, grain production tended to level off at either 22 kg P ha⁻¹ or 88 kg P ha⁻¹, regardless of whether the experiment was grown under rainfed or irrigated conditions (Figure 2.4c and d).

The discrepancy obtained in the comparison of predicted grain yield during the 1994 season with that measured from the field was mainly due to a higher percentage of seed being infected by aschochyta blight and the rodent attack on the crop toward crop harvest maturity. The higher yield variability under rainfed conditions is attributed to water stress during the grain filling phase and P stress which was as high as 0.5 even in plots that received high levels of P fertilizers. In general, the actual seed yield was constrained by soil water deficit, P stress, disease and pest attack.

Figures 2.5a and b, and 2.6a and b compare the simulated and field measured biomass (kg ha⁻¹) accumulation in both seasons. Significant differences were observed among treatments in the rate of total dry matter production by the bean crop. The simulated and field measured data shows that the control plots had the lowest values. The rate of dry matter accumulation prior to flowering, as indicated by the slope of the growth curve, was progressively lower with all treatments. After the flowering stage, the rates became very different between treatments indicating the effect of the P treatments applied. The simulated and field measured biomass accumulation increased as the LAI increased until between 42 DAP and 56 DAP. Thereafter, field measured biomass production started to decrease. These results were mainly due to the decrease in plant population at harvest maturity (Appendices 5a and 5b), and as reported by Hanway and Weber (1971), also due to rapid leaf and petiole fall which began after R₅ growth stage.

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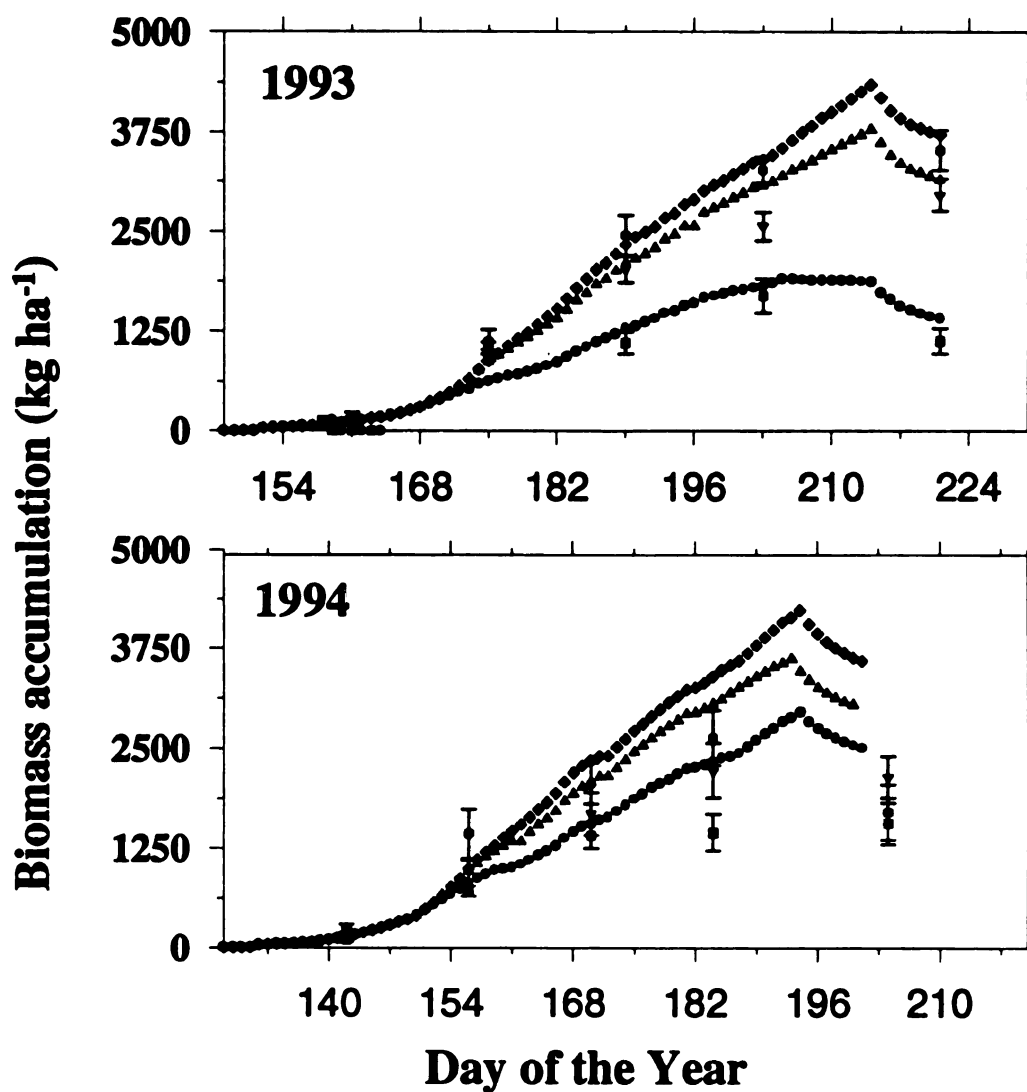
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The model predicted the patterns of dry matter accumulation accurately in most treatments under irrigated conditions and applied with P in form of TSP (Figs. 2.5a and b). However, plots treated with P in the form of MPR, under rainfed conditions, gave inconsistent results (Figs. 2.6a and b). The rainfed conditions compared to irrigated conditions due to the poor rainfall distribution pattern that occurred after the R_4 growth stage. This is more evident during the 1994 growing season (Figure 2.3).

At harvest maturity (R_9), a large proportion of the harvested crop was comprised largely of pods, followed by stems, and finally leaves. In contrast, the simulated biomass values did not decrease very much toward maturity, especially under irrigated conditions. The main reasons for such results are that the current model does not account for yield loss due to pests and diseases (Hoogenboom *et al.*, 1994), and other microclimatic factors are not considered in the model. Currently, the biomass accumulation declines toward maturity only by protein remobilization and leaf senescence.

Biomass accumulation (kg ha⁻¹)

Figure 2.5a.
under irriga

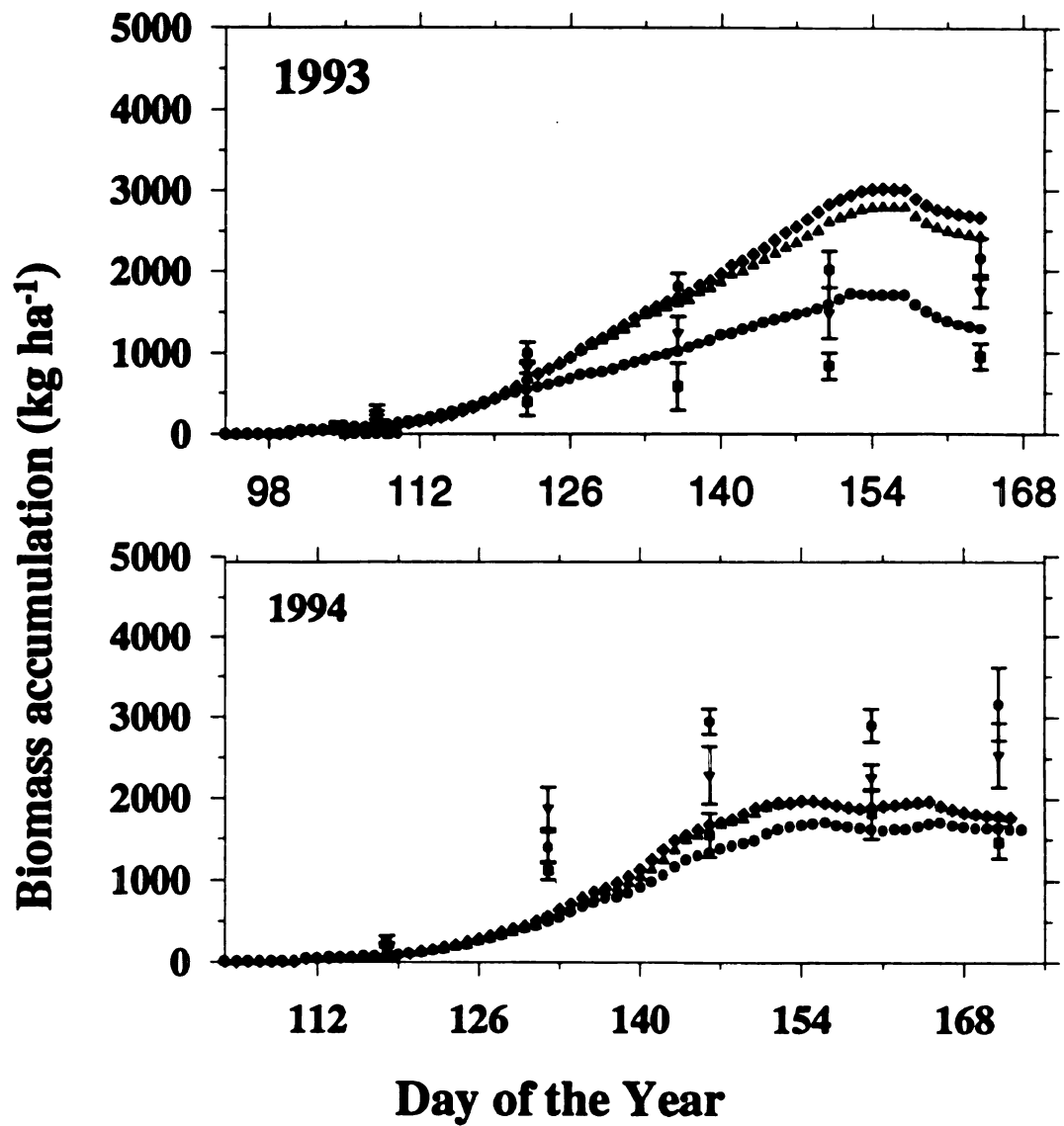


- Control simulated
- Control measured
- ▲ 22 kg P ha⁻¹ simulated
- ▼ 22 kg P ha⁻¹ measured
- 44 kg P ha⁻¹ simulated
- 44 kg P ha⁻¹ measured

Figure 2.5a. Simulated and measured biomass accumulation with application of TSP fertilizer under irrigated conditions. Vertical bars represent standard errors of the mean.

Biomass accumulation (kg ha⁻¹)

Figure 2.5b
under rainfed

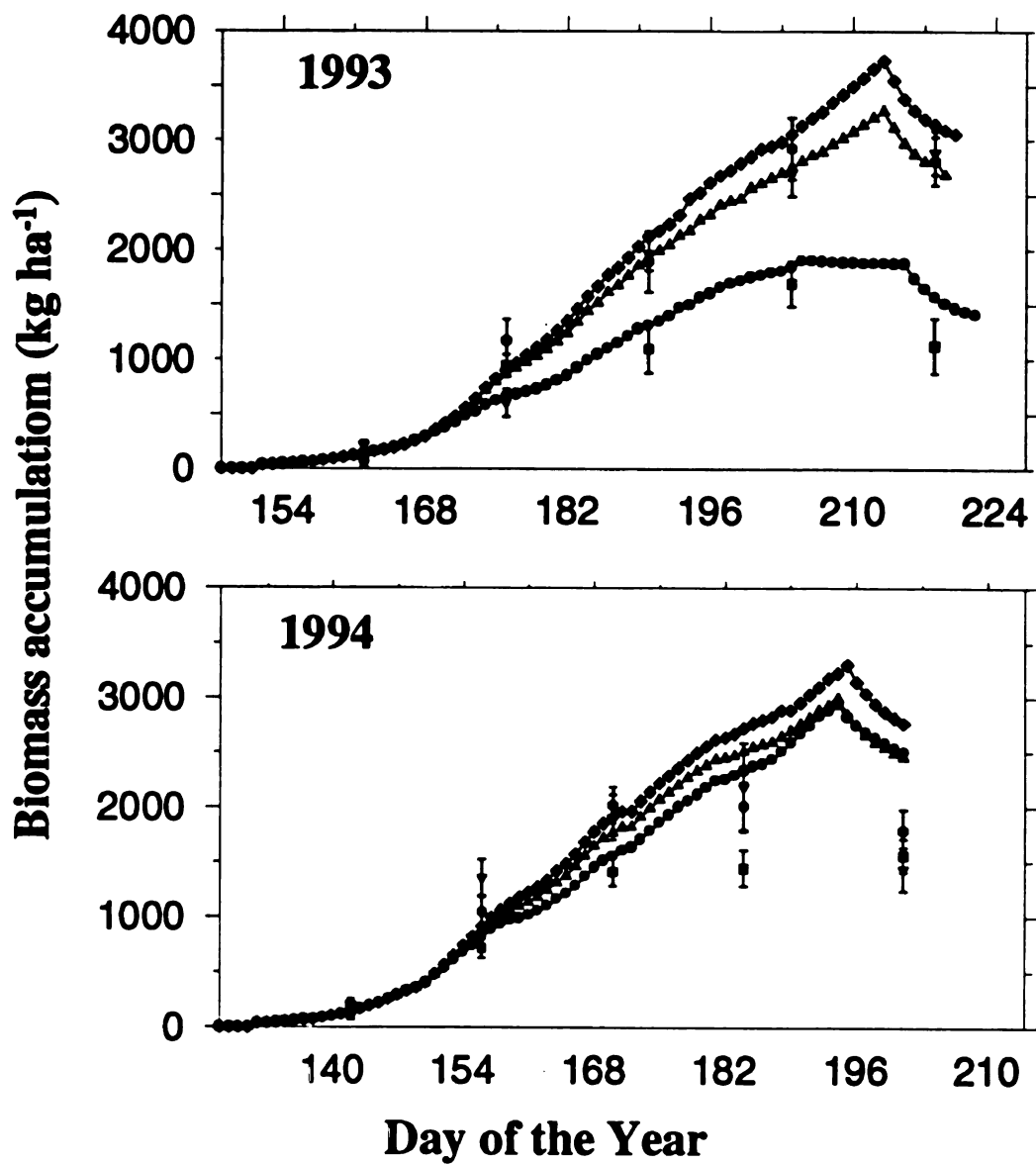


- Control simulated
- Control measured
- ▲ 22 kg P ha⁻¹ simulated
- ▼ 22 kg P ha⁻¹ measured
- 44 kg P ha⁻¹ simulated
- 44 kg P ha⁻¹ measured

Figure 2.5b. Simulated and measured biomass accumulation with the application of TSP under rainfed conditions. Vertical bars represent standard errors of the mean.

Biomass accumulation (kg ha⁻¹)

Figure 2.6a
under irriga



- Control simulated
- Control measured
- 22 kg P ha⁻¹ simulated
- 22 kg P ha⁻¹ measured
- 88 kg P ha⁻¹ simulated
- 88 kg P ha⁻¹ measured

Figure 2.6a. Simulated and measured biomass accumulation with the application of MPR under irrigated conditions. Vertical bars represent standard errors of the mean.

Biomass accumulation (kg ha⁻¹)

Figure 2.6b.
under rainfed

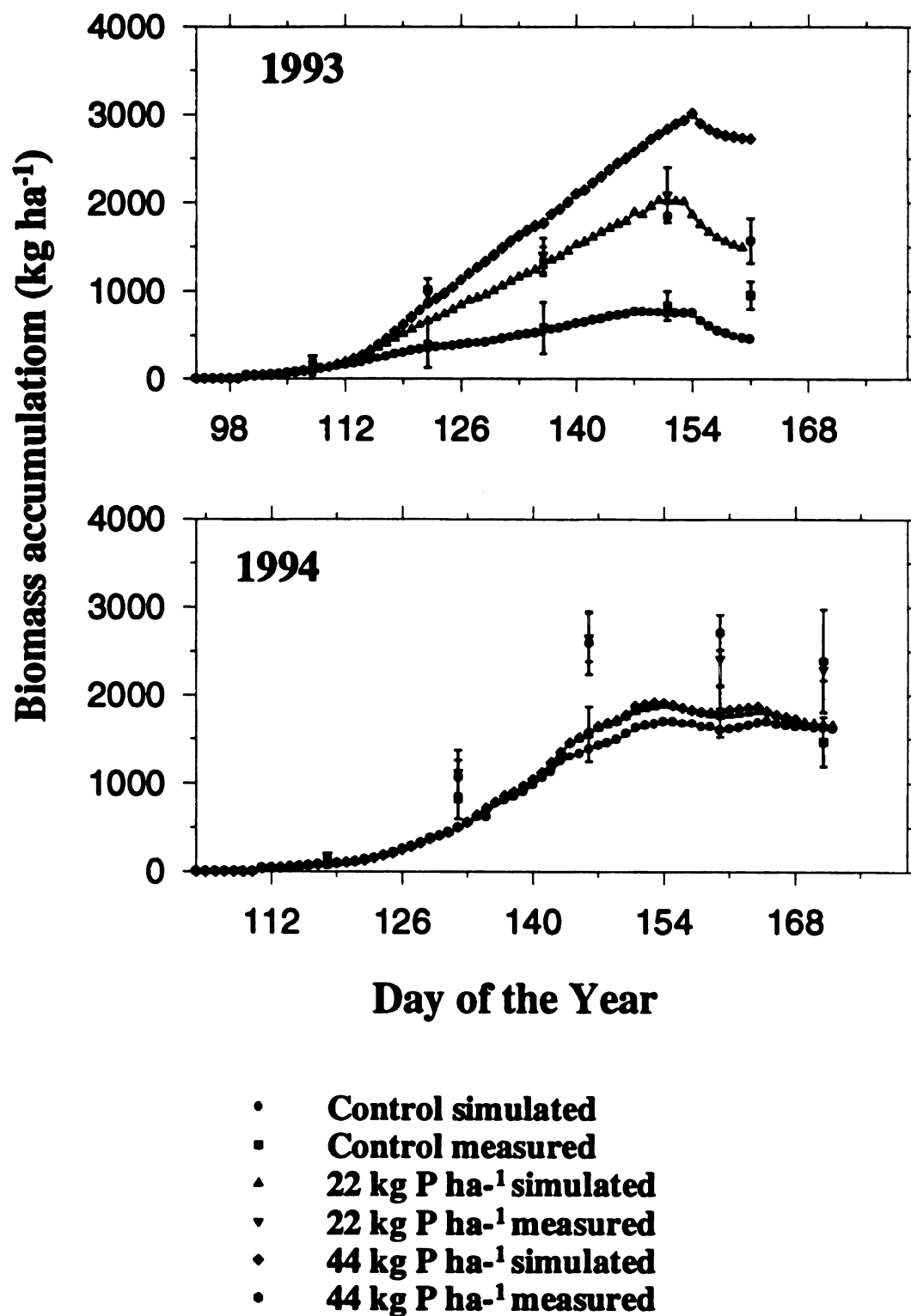


Figure 2.6b. Simulated and measured biomass accumulation with the application of MPR under rainfed conditions. Vertical bars represent standard errors of the mean.

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SUMMARY AND CONCLUSIONS

The bean model BEANGRO was calibrated, tested, and evaluated for predicting bean growth, development, yield and seed yield components as influenced by P fertilizer regimes in Tanzania. The systems simulation procedures used in this study showed how decisions regarding bean production in Tanzania can be made using the BEANGRO bean model. This study allowed the assessment of bean production system components effects and their interactions on bean yield.

As stated by Saka *et al.* (1990), slight over prediction of yields by the model, as found during this study, is generally expected because control of experimental factors to which the model is sensitive can never be complete. However, since the BEANGRO model did not give consistent crop yield predictions under rainfed conditions, this shows that there can be problems in using this model in marginal areas of Tanzania. In addition, field conditions are usually worse than the ideal conditions under which simulations were run on the computer. Such observations show that the model needs more adjustments so as to be able to correctly simulate crop growth, development, and yield under rainfed conditions.

Therefore, it is concluded from this study that the bean crop model BEANGRO can be used confidently to predict the effects of P management and soil fertility regimes on the potential bean growth, development and yields under irrigated conditions. This may reduce the need for empirical field trials where there is sufficient minimum input data.

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RECOMMENDATIONS FOR FUTURE RESEARCH

According to Dr. Phillip Thornton (systems scientist at IFDC), there appears to be substantial interest in the formation of a regional working group on the use of crop simulation models in East Africa. Such a group could support skill development, and modeling activities by identifying important application of crop models, and facilitating information exchange. However, there is lack of support by the governments for crop modeling activities, thus, one way to increase support is by demonstrating the benefits of the applications of the crop models in the area.

Diseases such as rust (*Uromyces appendiculatus* var. *appendiculatus*), ascochyta blight (*Phoma* spp), and pests such as leaf beetle (*Ootheca beningseni* Weise), bean fly (*Ophiomyia phaseoli*) are major factors in bean yield reduction, therefore, their effects need to be incorporated in the model.

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CHAPTER 3

SIMULATION OF PLANT AND SOIL PHOSPHOROUS DYNAMICS IN BEAN CROP GROWN UNDER RAINFED AND IRRIGATED CONDITIONS

ABSTRACT

Knowledge of nutrient uptake, distribution, and accumulation in a plant is important for basic understanding of its nutrition. The objectives of this study were to evaluate the effects of P fertilization on uptake, partitioning, and accumulation pattern of P throughout the growth cycle of bean crop grown on acid soils. Also the study results were to be used in evaluating the P version BEANGRO model in prediction of the plant P concentration (%), and accumulation (uptake) at various growth stage by comparing with those measured under field conditions. Different levels of triple superphosphate (TSP), and Minjingu phosphate rock (MPR) fertilizers were applied to the bean crop grown under rainfed and irrigated field conditions during the 1993 and 1994 growing seasons. Sampling for determining dry weights, and P concentration was done at V₃, R₁, R₅, R₇, and R₉ growth stages. Phosphorous concentration was analyzed in stems, leaves, pods, seeds, and shells. Increased P application resulted in slightly increased P concentration in all bean plant parts, and varied between experiments, treatments, plant parts, and crop age. MPR was not as effective as TSP in

supplying P to the bean crop. Large concentrations of applied P ranging from 0.27 to 0.47% were allocated to seeds. High levels of P did not result in Zn or Cu accumulation reduction. The critical P concentrations on dry weight basis at flowering in leaves were 0.23% under rainfed, and 0.35% under irrigated conditions.

The model predicted quite well the P accumulation in plots that received TSP under irrigated conditions. The current model over predicted the P uptake from plots applied with MPR fertilizer. The model was found to be very sensitive to the soil initial P conditions, and model parameters such as RCONST (i.e., rate of movement between active P and stable P pools), FPO_4 (i.e., P fraction used to calculate the plant P uptake, kg P ha^{-1}) and RPO_4U (i.e., the plant potential uptake from the soil). With very low initial soil P, the crop did not absorb P with the application of low and medium P fertilizer.

LITERATURE REVIEW

In agriculture the phosphorous (P) problem is threefold. First, the total P level of soil is low, about 200 to 2000 kg P per hectare-furrow slice (HFS) with an average of about 1000 kgP HFS⁻¹. Second, the native P compounds are mostly unavailable for plant uptake, some being highly insoluble. Third, when soluble sources of P such as those in fertilizer, and manure are added to soils, they are fixed or are changed to unavailable forms (Brady, 1990). Since the amount of plant available P at any given time is low (about 0.01% of total P) in the soil, to obtain high yields, farmers commonly apply more P in fertilizers than is required by crops.

Initially only the P in the solution can be taken up by the plant. However, as this is removed, it is replenished by more P coming into solution from the labile pool of P. When in the soil solution phosphorous is primarily in the form of orthophosphate ions, (H_2PO_4^- and HPO_4^{2-}). It is absorbed generally as the monovalent ion, (H_2PO_4^-), and less as the divalent ion, (HPO_4^{2-}), which is more prevalent of the two at neutral pH or above. However, the rate at which H_2PO_4^- is converted to HPO_4^{2-} in solution is so rapid that plants have little difficulty obtaining the necessary P for growth, even in soils with pH of 8 or higher (Foth and Ellis, 1988). Insolubility of P occurs at both extremes of the soil pH range (Lindsay and Moreno, 1960). Maximum P availability to plants is obtained when the soil pH is maintained in the range of 6.0 to 7.0.

Phosphorous functions in all biological processes, in high energy compounds and in mechanisms of energy transfer. Phosphorous in crop plants is as a component of important structures such as phospholipids in membranes, phosphorylated sugars and proteins, and as an integral part of nucleotides such as DNA (deoxyribonucleic acid), and RNA (ribonucleic acid) which carry the inheritance characteristics of living organisms. Phosphorous is also a component of energy transfer molecules such as adenosine diphosphate (ADP), and adenosine 5'-triphosphate (ATP); nicotinamide adenine dinucleotide (NAD); reduced, nicotinamide adenine dinucleotide diphosphate (NADPH) (Bieleski and Ferguson, 1983), and phosphoenolpyruvate (PEP).

Phosphorous is also important in C metabolism in plants. A first step in C fixation is the capture of light energy by the leaf. Lauer *et al.* (1989) observed that leaves of soybean that were deficient or low in P showed paraheliotropism (i.e., avoided sunlight by keeping the leaf edge toward the sun during the daylight. However, plants with adequate P levels

exhibited diaheliotropism (i.e., tracked the sun during the daylight hours). They also absorbed that carboxylation efficiency, and other parameters of photosynthesis decreased in low P plants. Other roles of P in crop plants are N fixation; crop maturation (flowering and fruiting, including seed formation); and root development.

Several factors regulate the P uptake in plants under field conditions. These include soil and climate factors, fertilizer type, crop effects, and management practices. Factors such as extensive root system, volume the soil in contact with the roots, soil moisture, aeration, temperature, physical and chemical properties of the soil are very important for nutrient uptake. Evidence from experimental results shows that P absorption takes place freely at all locations of the root surface (Clarkson and Hanson, 1980). As plant roots push their way through the soil they come in contact with the P in solution. Since the roots of the growing plants have a high demand for P, phosphate is absorbed by the roots at a high rate, and the soil solution in the direct root vicinity is depleted of P. This depletion creates a gradient between the P concentration near the root surface, and the P concentration in the soil (Mengel and Kirkby, 1987). Therefore, diffusion is important for P uptake because of its low concentration in the soil solution. It has been estimated that the distance of diffusion per day through soil at field capacity to root is 0.004 cm for the phosphate ion, H_2PO_4^- (Foth and Ellis, 1988). Large genetic variation for P uptake has been reported in tropical bean genotypes. Andean origin (large-seeded) germ plasm such as Canadian Wonder cultivar appears to have superior P efficiency under low P availability, while Mesoamerican genotypes are more responsive to applied P (Yan *et al.* 1995a, b).

There is still some controversy about whether H_2PO_4^- enters the cell via symporters or is driven by primary pumps. According to Ullrich-Eberius *et al.* (1981), Tu *et al.* (1990),

and Mimura (1995); P is taken up as H_2PO_4^- by means of an active mechanism with H - ATPase cotransport or HCO_3^- antiport properties. Since P is a multi-valent moiety, its charge changes with pH. In the value where pH is around 5, P is present as H_2PO_4^- and in the cytoplasm where pH is around 7.5, P is present as HPO_4^{2-} . Which ionic species of P is translocated across the tonoplast (Mimura, 1995) is not known. Once H_2PO_4^- is absorbed by the roots it is carried to the shoots by the symplastic pathway. Within a short time of uptake, the P absorbed is incorporated into organic compounds, mainly hexose phosphates and uridine diphosphate (Jackson and Hagen, 1960).

Under P stress, plants are capable of morphological, and physiological adaptations during the development that may substantially improve P acquisition. These adaptations include changes in P, and dry matter partitioning that favor growth of roots over shoots, and the induction of a high-affinity P uptake, and transport system in roots (Ogata *et al.*, 1988). Plants can also excrete acid phosphatase by roots to enhance acidification of the rhizosphere by plasma membrane-associated ATP-ase which may increase the dissolution of P-containing compounds, thus improving P uptake from the soil (Clarkson, 1985; Goldstein *et al.*, 1988 a, b). Increase in root formation, extension and root hair formation does also enhance the P uptake (Clarkson, 1985).

Research work has shown that availability of P from soil and applied P can be increased by inoculation with bacteria. Microorganisms such as *Escherichia coli* have a P scavenging system known as *pho* regulon. This is the system of genes whose expression are co-regulated by the P status in the organism. These genes are activated when the P becomes limiting, and encode proteins which include phosphatases which are P transporter (Torriani-Gorini, 1987). In plants there is a similar system to *pho* regulon (Goldstein *et al.*, 1989).

Phosphorous transport into roots, and cells of plants such as *Brassica* spp (Lefebvre *et al.*, 1990), maize (Lee *et al.*, 1990), and water fern (Bieleski and Lauchli, 1992), is enhanced by P deficiency, and phosphatases. Therefore, under P deficiency there is increase in acid-phosphatase activity in various parts of the plant (Bieleski, 1973), an increase in secretion of acid phosphatases from roots (Goldstein *et al.*, 1988 a, b). More recent studies have shown that *pho1* (Poirier *et al.*, 1991), and *phos2* (Delhaize and Randall, 1995) in mutations of *Arabidopsis thaliana* genes are involved in regulating the uptake of P in plants.

The effect of vesicular-arbuscular mycorrhizal fungi (VAMF) on plant P uptake has been extensively studied and reviewed (Kucey, 1987; Kucey *et al.*, 1989; O'keefe and Sylvia, 1991; McArthur and Knowles, 1993a, b; Khalil *et al.*, 1994). From greenhouse and field study results, it appears that the major action of mycorrhizal fungi in facilitating plant P uptake is to increase the absorptive surface area of the mycorrhizal root system, and to extend the P depletion zone away from the root surface (Kucey, 1987; Kucey *et al.*, 1987). Working with soybean, Karunaratne *et al.* (1986) observed that P efflux at low P solution concentration was lower for mycorrhizal than nonmycorrhizal roots. They concluded that mycorrhizal roots can remove P from soil solutions having lower P concentrations than nonmycorrhizal roots. This was mainly due to the mycorrhizal roots having lower C_{min} value (the solution concentration of an ion at which efflux equals influx) as shown by the Silberbush and Barber model (Silberbush and Barber, 1983). The concentration of P in plant tissue ranges from 0.15% to 1% of the dry weight of most crops with variation depending on crop species, age, plant parts, part position on the plant, soil fertility, water regimes, seasonal effects, and crop management (Jones *et al.*, 1991). Phosphorous concentration of less than 0.40% or 4000 ppm in foliar tissue of bean is regarded as being deficient, and 0.40-0.60% or

4000–6000 ppm as being adequate (Piggot, 1986), while greater than 1.00% is classified as excess (Jones *et al.*, 1991). A study conducted in East Africa by Wortmann *et al.* (1992) indicated that the previously recommended foliar critical nutrient level (CNL) of 0.25% for P was too low to be useful in predicting responses to applied fertilizers for bean crops grown in the test environments of that region. Predictions based on levels of 0.32% P were found to be more accurate.

There are numerous investigations which report on methods of improving the P availability, and uptake of P from PRs. These include the granule size and partial acidulation of PRs (Khasawneh and Doll, 1978; Hammond *et al.*, 1986; Chien and Hammond, 1988). A mixture of PRs and TSP in P ratio of least 1:1 has also been reported to increase the P uptake in maize (Chien *et al.* (1987), and in bean and rice (Menon *et al.*, 1991). Recent laboratory studies by Kpomblekou-A and Tabatabai (1994) have also shown that organic acids such as citric and oxalic acids have a potential as amendments for releasing plant available P and Ca from PRs applied to soils.

In the P model used in this study was adapted from Jones *et al.*, 1991 and Bowen, 1994, personal communication. The plant absorbs P from the labile pool. Labile P is defined as resin-extractable P, which is assumed to establish rapid equilibrium with an active mineral P pool following the addition or uptake of P. Phosphorus uptake studies from the soil are complicated by the fact that P is highly immobile element, and transport through soil to root surface is often a rate-limiting step. This problem is amplified by the dependence of the diffusion coefficient upon the soil type, P concentration, and soil moisture content (Amijee *et al.*, 1991).

The original model obtained from the International Fertilizer Development Center calculates the P value based on method of P extraction used (SMPX), the linear relationships given by Sharpley (1985); Sharpley *et al.* (1984, 1989) and soil groups as defined in the SOILPI subroutine. After the labile P pool (PRESIN) is defined, the active P pool (PACTIV) is calculated as a function of PRESIN, and a fertilizer P availability index (FPAI). Operating on a daily time step, the model calculates the changes in each of the P pools in the PCHEM subroutine. Although there are studies reported on the test of P model performance under field conditions in the USA using crops such as cotton, sorghum, wheat and maize (Jones *et al.*, 1984; Sharpley *et al.*, 1989; Jones *et al.*, 1991), there is no such study reported using the bean as test crop.

Bean plants are known to respond to applied fertilizer P more than other nutrients (Thung, 1991). Furthermore, PRs can be a good source of P (Chien and Hammond, 1988; Sale and Mokuwonye, 1993). In this study, it is suggested that the P simulation model, in conjunction with measurements of initial P status and pertinent soil and bean crop constants, may be a better tool for predicting P fertilizer requirements of bean crops than soil or plant tissue testing.

Therefore, the objectives of this study were: (I) To evaluate the uptake, distribution, and accumulation of P throughout the bean crop growth cycle, on acid soils applied with different levels of TSP, and MPR fertilizers under rainfed and irrigated field conditions; (ii) To evaluate and improve the P version BEANGRO model in predicting the plant P concentration (%), and accumulation (uptake in kg ha^{-1}) at various bean growth stages, and different plant parts by comparing with those measured under field conditions. The

information obtained is useful in improving the P fertilizer use, estimates of P decreases from the top soil, and consequently bean yield.

MATERIALS AND METHODS

Data were obtained from experiments conducted at Sokoine University of Agriculture (SUA), in Morogoro, Tanzania. Details on both sites, and experimental management are provided in Chapter 2. Plant materials used for tissue analysis were sampled from all three blocks. These included block A (used for assessing fresh applied P in 1993, and for residual P in 1994), block B (used for assessing annual applied P), and block C (used for assessing fresh applied P in the 1994 season).

Plant samples from stems, leaves (including petioles), pods, seeds, and shells were collected during the biomass harvest times. Samples were collected at V_3 , R_1 , R_3 , R_7 , and R_9 growth stages (Fehr *et al.*, 1971; Nuland and Schwartz, 1989) descriptions. Sampling for plant tissues was done from five plants per plot at each sampling time. Sampling and preparation for analysis were done as described by Jones *et al.* (1991). This was done by cutting the plants at the base of the stem. The samples were dipped in water to remove all soil, and separated into leaves, stems, and reproductive parts (pods) for N (for 1993 season) and P determination (for both seasons). At maturity pods were shelled; seeds and shells were also analyzed for P concentration. Only the youngest, fully developed trifoliolate leaves, and mature (fully expanded) leaves from the top, and middle part of the plants were sampled. Leaf samples taken at flowering (R_1) were also used to determine the contents of P, K, Ca, Mg, and different micronutrients in the bean foliar tissues.

The subsamples were dried at 70°C, ground to pass through a 40-mesh sieve using a WILEY MILL model 3383-L20. A ground plant tissue of 0.3 grams was used for wet acid digestion using 3ml concentrated H_2SO_4 , and 30% H_2O_2 as oxidants, and LiCl at 1000 ppm for temperature elevation (Parkinson and Allen, 1975). After digestion, aliquots were used for analysis. Concentrations of P in the same digested samples were determined by the ammonium molybdate-ascobic acid method (Murphy and Riley, 1962).

Calcium and other nutrients' concentrations were analyzed only for 1994 season. Nitrogen and P were analyzed using the Skalar autoanalyzer at IFDC laboratories in Muscle Shoals, Alabama for 1993 plant tissues. Phosphorous at V_3 , R_3 , R_7 , and R_9 growth stages from 1994 season was determined using methods described by Murphy and Riley (1962), using the Lachat analyzer in Crop and Soil Sciences laboratories at Michigan State University, East Lansing. The 1994 foliar tissues were analyzed for P, K, Ca, Mg, Fe, Al, Zn, Cu, and Mn at flowering using the inductively coupled plasma emission spectrometry procedures at Michigan State University.

Due to the time and the financial constraints, plant sampling was done for all treatments, but not in all experimental plots. Therefore, statistical analyses for nutrients analyzed in this study were not conducted. Phosphorous concentration in leaves, stems, pods, seed, and shells were used with the leaf, stem, pod, seed, shell, and dry weight to calculate the P total accumulation. Nutrient concentration (i.e., nutrient content per unit dry matter), and nutrient accumulation (i.e., nutrient concentration x dry matter per unit area) at different growth stages, and plant parts were determined as a function of source, and rate of fertilizer used for the dates when samples were collected. Further, maximum and minimum P concentration values determined for leaf, stem, seed, and shell were used for cultivar

coefficient calibration in the species file (SPE) as described in Chapter 2. Data from annual applied P plots were used for calculation of P accumulation (on per hectare basis). The critical concentrations were estimated at 95% of the maximum yield after plotting the dry weight at maturity against the P concentration in plant leaves at early flowering from rainfed, and irrigated experiments as described by Ogata *et al.* (1988).

Phosphorous Model Calibration and Modification

The model for phosphorous dynamics added to the BEANGRO model was an adaptation of that presented by Jones *et al.* (1984) and Sharpley *et al.* (1984). Their model structure was not changed. However, refitting some constants in the equations was necessary for the model to best describe the results obtained from the field experiments conducted in Tanzania. Thus, some of the constants described below for the various subroutines will not be the same as those described by Jones *et al.* (1984) and Sharpley *et al.* (1984).

Initial Soil P (Subroutine SOILPI)

This subroutine is used to initialize the soil P pools. First, simulations were run and calibration of the existing model in terms of P concentration (%), and total accumulation (kg ha⁻¹) in shoots and grain was made so that the model simulated bean response to soil P accurately. Bray I (SMPX IB002) method was used for soil test to estimate labile P, on the highly weathered soils (SGRP IB003) for the two sites used for this study.

After calibrating the model using the genetic coefficients (Chapter 2), the second step was to do the calibration using the control treatment and the soil initial P conditions of the 1993 irrigated experiment.

Using the $PRESIN = 0.14 * BRAYI + 4.2$ relationship provided by Sharpley *et al.* (1984) for predicting the labile P (PRESIN which is the pool responsible for P absorbed by the plant) in the model; labile P (kg P ha⁻¹), and the plant P uptake (kg P ha⁻¹) were found to be over predicted by the model. Therefore, a new relationship with a forced zero intercept was developed (by Dr. Joe T. Ritchie) using the same data provided by Sharpley *et al.* (1984) for highly weathered soil as follows:

$$PRESIN = 0.203 * BRAYI$$

where

PRESIN = Labile P which is absorbed by the plant

BRAYI = Amount of P measured by BRAY I for the specific soil layer

After the labile P pool was defined, active P pool (PACTIV) was calculated as a function of PRESIN and fertilizer P availability index (FPAI). FPAI represents the fraction of fertilizer P remaining as labile P after incubating fertilizer P and soil for six months (g extracted / g P added to soil).

For the highly weathered soil used in this study, FPAI was calculated as follows (Jones *et al.*, 1984):

$$FPAI = (-0.047 * CLAY) + (0.0045 * PRESIN) - (0.053 * OC) + 0.39$$

where,

CLAY = Amount of clay (%)

OC = Organic carbon (%)

The FPAI value from this calculation for the soils in this study came out to be about 0.23. After testing the model using $FPAI = 0.23$, results showed that the value needed to be much smaller for the biomass and soil phosphorous measurements to agree with the simulations. Using a value of $FPAI = 0.08$ provided the best fit. This value is similar to ones reported in Jones *et al.*, (1984) for less acid soils. Thus, this value was used in all the model calculations for this experiment.

After the FPAI had been calculated, it was used to determine the initial size of PACTIV as follows:

$$PACTIV = PRESIN * ((1.0 - FPAI) / FPAI)$$

The stable inorganic P pool (PSTABLE) was assumed to be four times as large as the active P pool at equilibrium as described by Jones *et al.* (1984) and calculated as follows:

$$PSTABLE = PACTIV * 4.0$$

Soil Phosphorous Transformations (Subroutine PCHEM)

This subroutine calculates the rates of movement between different inorganic P pools, then updates each pool based on the calculated values. The rate of movement (PRTOPA) from PRESIN to PACTIV was calculated as follows:

$$PROTOPA = 0.18 * (PRESIN - PACTIV * (FPAI / (1.0 - FPAI)))$$

If the value of PROTOPA is negative, indicating flow from the active to the resin pool, the slower movement between these pools is calculated as:

$$PROTOPA = PROTOPA * 0.1$$

Since PSTABLE was assumed to be four times as large as PACTIV at equilibrium, the equation describing the rate of movement between the two pools (PATOPS) used was as follows:

$$PATOPS = RCONST * ((4.0 * PACTIV) - PSTABLE)$$

where

RCONST = rate of P movement that varies with soil type

For highly weathered soils RCONST was calculated as a function of FPAI described by Sharpley *et al.* (1984):

$$RCONST = EXP (-1.77 * FPAI - 7.05)$$

If the value of PATOPS is negative, indicating flow from the stable to active pool, the slower movement between these pools is calculated as:

$$PATOPS = PATOPS * 0.1$$

After the rate of P movement between pools had been determined, each pool was updated.

Phosphorous Uptake (Subroutine PUPTAK)

This determines the P uptake by plant. The phosphate fraction (FPO_4) used for plant uptake was calculated as follows:

$$FPO_4 = 1.0 - EXP (-0.5 * (PRESIN - 0.3))$$

$$RPO_4U = RFAC * FPO_4 * 0.02$$

where

RPO_4U = potential P uptake from a soil layer ($kg\ P\ ha^{-1}$)

RFAC = interim variable describing the effects of water stress and root length density on potential P uptake from a soil layer calculated as:

$$RFAC = RLV * SMDFR * DLAYR$$

where

RLV = root length density for soil layer (cm root/cm³ soil)

$SMDFR$ = the deficit factor affecting P uptake at low soil water (unitless) was calculated as:

$$SMDFR = (SW - LL) * 10.00, \quad LL > SW > LL + 0.10$$

$$SMDFR = 0, \quad SW < LL$$

$$SMDFR = 1, \quad SW > LL + 0.10$$

where:

SW = soil water content

LL = soil water content at the lower limit

$DLAYR$ = thickness of the soil layer (cm)

If TPS is added to the soil, the value of RPO_4U as calculated above is multiplied times 2. This is done to simulate the priming effect by the TPS to increase root activity and increase uptake at the same P concentration.

Model Testing

After calibrating the P model, simulations were made and predicted results were compared with field measured values. The model was tested for its performance using data from the control, 22, 44, and 88 kg P ha⁻¹ treatments in form of TSP and using the control, 22, 88, and 176 kg P ha⁻¹ from both experiments of the 1993 and 1994 cropping seasons.

RESULTS AND DISCUSSION

General Observations

Values for N concentration are shown in Table 3.1. Nitrogen concentration was highest at V₃ in the youngest leaves with the values of 2.29 under rainfed conditions, and 3.89% under irrigated conditions. The leaf N concentrations ranged from 2.90 under rainfed experiment to 3.89% under irrigated conditions. These values are slightly lower than those observed by Salema (1987) who reported the values ranging from 3.56 to 4.60% from results of an experiment conducted at the same location (SUA farm) using a similar cultivar. The high leaf N values reported by Salema (1987), may have mainly been due to the application of urea fertilizer at 80 kg N ha⁻¹ at sowing, and the double strain inoculum of *Rhizobium leguminosarum* biovar *phaseoli* applied to the seeds before sowing. The seed-rhizobial inoculation may have been an additional factor to the leaf N concentration.

The pod N concentration was highest at R₃ (in the youngest pods) with values of 4.62% under rainfed, and 3.45% under irrigated experiment. The pod N concentration in this study was also lower than that reported by Salema (1987). At R₆ the concentration started to decrease. The decrease of pod N concentration with age observed in this study compared favorably with the results by Westermann *et al*, (1985) for beans grown under greenhouse conditions. Such results were due to the increase of the larger quantity of pod biomass which resulted in dilution effect.

Seed N concentration was lower under rainfed conditions (3.07%) than under irrigated conditions (3.75%). The seed N values reported here under irrigated conditions agree favorably with those given by Thung (1991) for the bean crop grown under field

conditions. The shell N content were similar in both experiments, with values of 0.68%.

Table 3.1. Nitrogen content at five different bean growth stages in the 1993 season.

Growth stage	Nitrogen concentration (%)	
	<u>Experiment</u>	
	Rainfed	Irrigated
Leaf N at V ₃	2.90	3.89
Leaf N at R ₁	2.02	3.80
Leaf N at R ₃	3.19	3.05
Leaf N at R ₇	1.58	2.06
Leaf N at R ₉	1.50	1.56
Pod N at R ₃	4.62	3.45
Seed N at R ₉	3.07	3.75
Shell N at R ₉	0.68	0.68

Phosphorous Concentration and Distribution in the Plant

Field measured concentration of P in different parts of the bean crop at different growth stages are shown in Table 3.2. Results on P concentration from both seasons show that irrigated experiment had higher P concentration in all plant tissues at all stages of sampling. These results are supported by Begg and Turner (1976) who reported that there is more rapid increase in nutrient uptake rates than plant growth rates when adequate water was supplied to crops. Such results may also have been due to lower temperatures experienced during the growth of the irrigated experiment (Figure 2.1).

Table 3.2 Phosphorous concentration (%) in different parts of bean plants as influenced by different fertilizer sources and levels of P application.

Treatment	Crop Age (DAP)	Stems	Leaves	Pods	Seed	Shells
<u>Rainfed experiment</u>						
0 kg P ha ⁻¹	14	0.09	0.20	-	-	-
	28	0.01	0.21	-	-	-
	42	0.03	0.10	0.09	-	-
	56	0.06	0.06	0.10	-	-
	Maturity	0.02	0.08	0.09	0.21	0.04
22 kg P ha ⁻¹ TSP	14	0.13	0.23	-	-	-
	28	0.06	0.35	-	-	-
	42	0.05	0.38	0.08	-	-
	56	0.03	0.05	0.12	-	-
	Maturity	0.02	0.04	0.11	0.25	0.02
22 kg P ha ⁻¹ MPR	14	0.13	0.17	-	-	-
	28	0.13	0.28	-	-	-
	42	0.05	0.02	0.08	-	-
	56	0.06	0.04	0.17	-	-
	Maturity	0.02	0.07	0.14	0.25	0.03
44 kg P ha ⁻¹ TSP	14	0.14	0.09	-	-	-
	28	0.15	0.23	-	-	-
	42	0.07	0.02	0.09	-	-
	56	0.06	0.03	0.17	-	-
	Maturity	0.02	0.05	0.18	0.34	0.07
88 kg P ha ⁻¹ TSP	14	0.16	0.32	-	-	-
	28	0.05	0.28	-	-	-
	42	0.09	0.13	0.12	-	-
	56	0.03	0.09	0.18	-	-
	Maturity	0.03	0.04	0.15	0.27	0.04
88 kg P ha ⁻¹ MPR	14	0.14	0.14	-	-	-
	28	0.15	0.22	-	-	-
	42	0.04	0.03	0.10	-	-

Table 3.2 cont.

	56	0.02	0.04	0.11	-	-
	Maturity	0.02	0.03	0.11	0.22	0.01
176 kg P ha ⁻¹ MPR						
	14	0.34	0.09	-	-	-
	28	0.13	0.25	-	-	-
	42	0.05	0.06	0.08	-	-
	56	0.06	0.07	0.22	-	-
	Maturity	0.13	0.02	0.13	0.30	0.02

Irrigated experiment

0 kg P ha ⁻¹	14	0.12	0.13	-	-	-
	28	0.15	0.15	-	-	-
	42	0.08	0.02	0.12	-	-
	56	0.02	0.10	0.17	-	-
	Maturity	0.04	0.04	0.16	0.34	0.07
22 kg P ha ⁻¹ TSP						
	14	0.17	0.33	-	-	-
	28	0.06	0.48	-	-	-
	42	0.09	0.23	0.18	-	-
	56	0.05	0.07	0.17	-	-
	Maturity	0.04	0.09	0.14	0.27	0.01
22 kg P ha ⁻¹ MPR						
	14	0.22	0.32	-	-	-
	28	0.17	0.35	-	-	-
	42	0.11	0.14	0.09	-	-
	56	0.05	0.05	0.17	-	-
	Maturity	0.03	0.05	0.14	0.24	0.02
44 kg P ha ⁻¹ TSP						
	14	0.22	0.35	-	-	-
	28	0.16	0.37	-	-	-
	42	0.15	0.14	0.14	-	-
	56	0.06	0.12	0.15	-	-
	Maturity	0.04	0.08	0.13	0.34	0.01
88 kg P ha ⁻¹ TSP						
	14	0.24	0.33	-	-	-
	28	0.08	0.43	-	-	-
	42	0.06	0.24	0.16	-	-
	56	0.08	0.11	0.21	-	-
	Maturity	0.06	0.03	0.17	0.47	0.01

Table 3.2. (cont'd)

88 kg P ha⁻¹MPR						
14	0.12	0.31	-	-	-	
28	0.16	0.30	-	-	-	
42	0.10	0.09	0.13	-	-	
56	0.07	0.07	0.18	-	-	
Maturity	0.04	0.06	0.17	0.33	0.01	
176 kgP ha⁻¹MPR						
14	0.21	0.27	-	-	-	
28	0.18	0.38	-	-	-	
42	0.10	0.25	0.17	-	-	
56	0.03	0.09	0.20	-	-	
Maturity	0.04	0.06	0.12	0.24	0.01	

DAP refers to days after planting

Maturity refers to harvest maturity.

Low temperatures are known to have significant effects on nutrient uptake, and accumulation through plant growth (Saito and Kato 1994). These conditions, during crop growth increase the immobility of nutrients such as P which results in concentration effect (Jarrell and Beverly, 1981). The present results show that, P concentration increased between V₃ and R₁ growth stages; similar results have been reported in pigeon pea by Adu-Gyamfi *et al.* (1990). Such results may have been influenced by the characteristics of the P fractions in bean plant in response to P supply during the two growth stages. Phosphorous concentration in bean tops decreased with crop age, but dry weight increased with P levels applied. Similar observations have been reported by Adu-Gyamfi *et al.* (1990) in pigeon peas. Phosphorous concentration was lowest in control plots and highest in plots that received TSP at 44 and 88

kg P ha⁻¹. Using the scale suggested by Piggott (1986), at flowering (R₁) stage, most plots indicated inadequate levels of P in bean crop.

The results of high P concentrations found in young bean tissues, and their decrease with age observed in this study agree with those reported in hardwood foliage by Lea *et al.* (1979). Such decrease in concentration with age is referred to as dilution effect (Jarrell and Beverly, 1981). Because of a lesser quantity of pod biomass at the same rate of P uptake, results show that the P concentration in pods increased as the pods grew older. This was true from R₂ up to R₅ growth stage. As expected, at R₅ growth stage, seeds began to develop in pods, pod biomass increased, and the value in P concentration decreased due to the dilution effects. As the seeds developed, P moved from the pod walls into the seeds where it is usually stored in form of phytate (Lolas *et al.*, 1976; Ogata *et al.*, 1988).

The leaves and stems decrease in P concentration started at R₁ growth stage. According to Mimura (1995), the concentration of P in the leaves is always higher than in older leaves under P deficiency due to its re-translocation from older leaves to younger developing tissues. Starting from R₁ growth stage, P was being remobilized from vegetative plant parts to developing reproductive structures such as flowers, pods, and seeds as suggested by Grabau *et al.* (1986); and Lauer and Blevins (1989) based on nutrient harvest indices observed in their studies using soybean. Similar observations have been reported by Adu-Gyamfi *et al.* (1990) using pigeon pea and soybean plants. In few instances plant tissues from control plots had higher P concentration than those tissues from plots which received fertilizers. These results could be due to the nutrient accumulation being higher than crop growth rate during that time of sampling.

Seeds had the highest P concentration compared to other plant tissues. This shows that the plants allocated the majority of their P reserves to seed development. Similar results have been reported by Grabau *et al.* (1986) in soybean, and by Fageria (1989) and Yan *et al.* (1995b) in beans. It is now known that in grains and seeds, P element is stored as phytate P, which accounts for 50 to 70% of total P in grains and seeds (Lolas *et al.*, 1976). Phytin, an insoluble Ca-Mg salt of phytic acid and Zn, Fe or K salts of phytic acid are formed in developing seeds during the period of rapid starch synthesis. During germination, phytase breaks down phytate within a short period releasing P and cations for the formation of membrane and other cellular constituents (Mukherji *et al.*, 1971).

Accumulations of K, Ca, Mg, Cu, Mn, Zn analyzed at flowering are shown in Table 3.3. Increase in leaf K, Ca, and Mg due to fertilizer effect reported in this study is in agreement with observations reported by Hallmark and Barber (1984) in soybeans, and those by Fageria (1989) in beans grown on Oxisol soils in Brazil. Literature shows that high levels of P application induces Zn deficiency in plants (Lonergan *et al.*, 1982; Singh *et al.*, 1988; Fageria, 1989; Moraghan, 1994). According to Millikan (1963), high levels of P in plant tissues inactivate the Zn requirements. However, in this study, high levels of P fertilizer did not have a significant effect on Zn and Cu uptake. Such results may have been due to low concentrations of P in plant tissues as revealed by the plant tissue analyses.

Table 3.3. Nutrient concentration in bean plant leaves at early flowering as influenced by different sources and levels of annual applied P fertilizer in the 1994 season.

Treatment	<u>Rainfed experiment</u>					
	K	Ca	Mg	Cu	Mn	Zn
	-----%-----			-----ppm-----		
0 kg P ha ⁻¹	2.11	1.98	0.63	13	149	46
22 kg P ha ⁻¹ -TSP	3.92	2.24	0.59	18	302	51
22 kg P ha ⁻¹ -MPR	2.37	3.54	0.68	16	216	53
44 kg P ha ⁻¹ -TSP	2.28	2.45	0.50	11	195	36
88 kg P ha ⁻¹ -TSP	3.69	2.73	0.61	17	225	45
88 kg P ha ⁻¹ -MPR	2.19	2.56	0.60	14	148	38
176 kg P ha ⁻¹ -MPR	3.99	2.61	0.54	17	976	87
<u>Irrigated experiment</u>						
0 kg P ha ⁻¹	2.96	1.65	0.54	22	113	46
22 kg P ha ⁻¹ -TSP	3.45	1.95	0.65	12	446	43
22 kg P ha ⁻¹ -MPR	3.38	2.10	0.74	19	613	53
44 kg P ha ⁻¹ -TSP	3.61	1.82	0.60	23	106	66
88 kg P ha ⁻¹ -TSP	3.36	2.01	0.68	13	109	41
88 kg P ha ⁻¹ -MPR	3.41	2.06	0.60	15	136	52
176 kg P ha ⁻¹ -MPR	3.81	1.84	0.57	24	690	62

Fe values were over-range by the method used for nutrient analysis.

Relationships between dry weight (g m⁻²) at maturity, and P concentrations of bean leaves at early flowering are shown in Figure 3.1. Critical P concentration values were 0.23% under rainfed, and 0.35% under irrigated conditions. The results on critical P concentration reported from irrigated experimental conditions agree with those reported by CIAT (1977), and Wortmann *et al.* (1992) for beans grown under East African conditions.

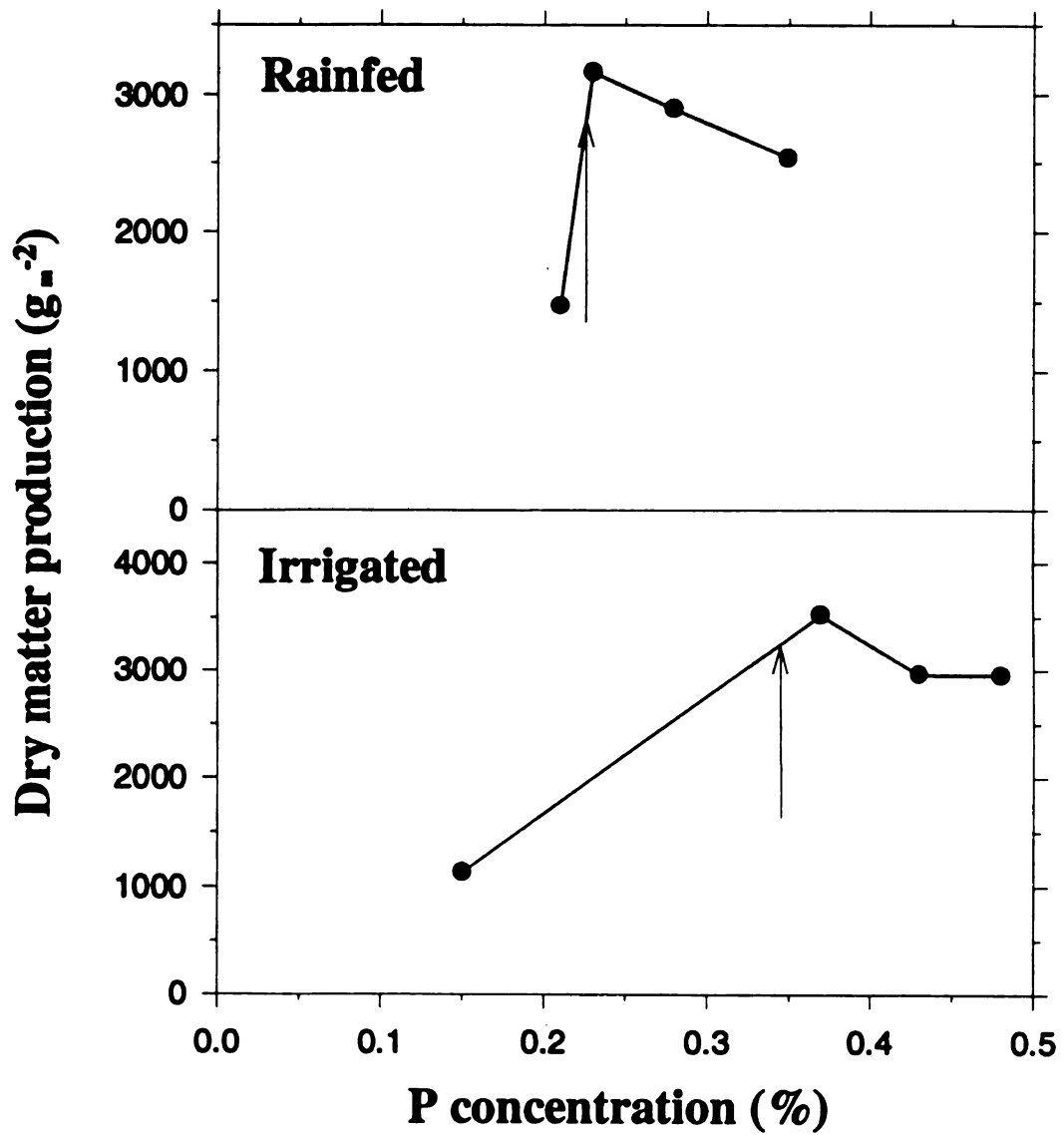


Figure 3.1. Relationship between dry matter production and phosphorous concentration at maturity. Arrows indicate values of critical P concentration.

Total Phosphorous Accumulation and Removal From the Field

The amount of P absorbed on per hectare basis was in the order of stem < leaves and < pods at R_3 . At physiological maturity (R_4), and at harvest maturity (R_5) the order was stem < shells < leaves < pods < seeds in both experiments. Phosphorous accumulation on per hectare basis was the product of the P concentration in the bean plant or plant part, and the dry matter produced per unit area. Although at V_3 growth stage the leaves had the highest P concentration; due to low dry matter production, the total P accumulation was very low. The total P accumulation was highest between R_1 and R_5 growth stages. This was also the time when dry matter production was also at maximum. After R_5 growth stage, there was a decrease in P accumulation. The decrease in P accumulation can be attributed to the decrease in dry matter production, and the lower P concentration caused by diluting effect by the increase dry matter produced (Jarrell and Beverly, 1981).

In bean growing areas of Tanzania, such as the Kagera Region young tender leaves known locally as "*Omushokolo*", and immature pods also known as "*Ebiendwa*" in the area, are usually harvested between R_1 and R_7 growth stages for vegetable consumption. This is especially so during the time when the bean grains are in short supply. Such time is usually after planting the last lot which was reserved for seed. The immature pods harvested between R_6 and R_7 are usually shelled, and immature seeds prepared for consumption.

At R_5 growth stage which is time for harvest, farmers harvest all aboveground parts of bean crop. Usually all the harvested plant parts are taken out of the field, to the homestead for threshing. Therefore, the nutrient taken out from the field is all that which is contained in the whole plant parts. Once at the homestead, the harvested crop is shelled, and the bean

straw is usually used to feed dairy animals. This practice is more important in areas around Mt. Kilimanjaro in the northern parts of Tanzania (Urio and Mlay, 1984; Shem *et al.*, 1988).

Table 3.4 shows the quantity of P nutrient which is removed from the field by harvesting different bean plant parts, at different growth stages. The results show that if the crop is harvested as green pods i.e., between R_3 and R_4 growth stages, the P removal can be as high as 8.7 kg P ha^{-1} . However, if the crop is harvested at R_5 growth stage, seed harvest may result in removal of about 6 kg P ha^{-1} from the field. Similar results were reported in Ghana by Rhodes (1995) who observed that with the use of NPK fertilizer, P removal from the fields was 27% by grain or tuber food crop harvest, and 42% was removed in crop residues. The amount of P removed from the field will depend on the amount of fertilizer applied, and on whether the crop is irrigated or rainfed as the present study results show. Nutrient accumulation in relationship to the amount of P applied shows that harvesting of bean crop at maturity, can result in 2 to 5% P removal from the field depending on the P fertilizer source, rate applied and final crop yield.

Table 3.4 Amount of phosphorous removed from the field by bean harvest (kg P ha^{-1}).

1993 season		1994 season		
<u>Leaf P accumulation at flowering (R₁)</u>				
<u>Treatment</u>	<u>Irrigated</u>	<u>Rainfed</u>	<u>Irrigated</u>	<u>Rainfed</u>
0 kg P ha ⁻¹	1.10	0.81	0.59	0.98
22 kg P ha ⁻¹ -TSP	2.11	1.21	3.28	1.58

Evaluation of Simulated Phosphorous Concentration and Accumulation

Comparison between simulated and field measured P concentration (%) at flowering stage is shown in Table 3.5. Comparison of these two sets of data shows that the simulated values were always larger than field measured values. Daily simulation results (data not shown) indicated that P concentration increased to about 0.50% at V_3 growth stage. After this growth stage the value dropped to about 0.05% depending on the experiment, treatment and plant part being assessed. The maximum P concentration was at V_3 growth stage while the minimum concentration was at R_9 growth stage for all treatments. A fairly accurate prediction of the grain P concentration in all experiments with TSP application and field measured results for both seasons was obtained at harvest maturity.

Since precautions were taken to avoid any analytical discrepancies, the low values of P measured under field conditions could be due to the fact that, although the crop received

more than enough fertilizer, the P was not readily available to the crop due to most of it being fixed by the soil. As discussed earlier, the other explanation could be that the crop diluted its P to a greater extent under field conditions (Jarrell and Beverly, 1981).

Comparison between simulated and field measured P accumulation (kg ha^{-1}) by the bean shoots treated by TSP fertilizer are shown in Table 3.6, while those treated with MPR fertilizer are shown in Table 3.7. In both experiments the control treatment had the lowest amount of P accumulation.

The field measured amounts of P accumulation were lower than the model predicted values at the flowering stage. However, at maturity harvest, model predicted values were higher than field measured values for plots treated with TSP fertilizer (Table 3.6). For plots that received P in form of MPR, the model predicted P accumulation was higher than the field measured values except for the results from the 1993 irrigated experiment (Table 3.7).

Table 3.5. Comparison between simulated and field measured vegetative P concentration (%) at flowering stage.

<u>Treatment</u>	<u>1993 season</u>				<u>1994 season</u>			
	<u>Experiment</u>				<u>Experiment</u>			
	<u>Rainfed</u>		<u>Irrigated</u>		<u>Rainfed</u>		<u>Irrigated</u>	
	<u>SIM¹</u>	<u>FM²</u>	<u>SIM</u>	<u>FM</u>	<u>SIM</u>	<u>FM</u>	<u>SIM</u>	<u>FM</u>
Control	0.12	0.27	0.14	0.29	0.23	0.16	0.16	0.15
22 kg P (TSP)	0.24	0.31	0.25	0.30	0.32	0.21	0.20	0.27
44 kg P (TSP)	0.28	0.30	0.26	0.34	0.32	0.19	0.22	0.23
88 kg P (TSP)	0.29	0.32	0.28	0.32	0.32	0.15	0.23	0.16
22 kg P (MPR)	0.21	0.33	0.20	0.29	0.30	0.23	0.16	0.27
88 kg P (MPR)	0.21	0.41	0.20	0.29	0.31	0.21	0.17	0.23

¹ SIM refers to simulated (model predicted) data

² FM refers to field measured (observed) data

Table 3.6. Comparison of simulated and field measured phosphorous accumulation (kg P ha⁻¹) in bean shoots at two growth stages with the application of triple superphosphate fertilizer.

	<u>Growth stage</u>							
	R_1^a				R_9^b			
	<u>1993 growing season</u>							
	R^c		I^d		R		I	
	<u>SIM^e</u>	<u>FM^f</u>	<u>SIM</u>	<u>FM</u>	<u>SIM</u>	<u>FM</u>	<u>SIM</u>	<u>FM</u>
Treatment								
Control	0.70	1.07	0.90	2.20	1.40	0.48	1.20	1.80
22 kg P ha ⁻¹	1.80	2.56	2.20	4.71	3.20	1.05	2.90	6.21
44 kg P ha ⁻¹	2.00	3.52	2.50	3.41	4.20	1.48	4.30	7.74
88 kg P ha ⁻¹	2.20	3.42	2.70	4.00	5.20	3.22	6.00	6.21
	<u>1994 growing season</u>							
Control	1.20	1.80	1.30	1.08	1.90	0.48	1.70	1.25
22 kg P ha ⁻¹	1.60	2.60	1.90	2.75	3.20	1.22	3.00	1.75
44 kg P ha ⁻¹	1.60	3.60	2.20	2.69	4.20	1.02	4.20	2.25
88 kg P ha ⁻¹	1.60	3.00	2.30	2.24	5.20	2.10	5.40	2.25

^a R₁ refers to flowering stage

^b R₉ refers to harvest maturity stage

^c R refers to rainfed experiment

^d I refers to irrigated experiment

^e SIM refers to simulated (model predicted) data

^f FM refers to field measured (observed data)

Table 3.7. Comparison between simulated and field measured phosphorous accumulation (kg P ha⁻¹) in bean shoots at two growth stages with the application of Minjingu phosphate rock fertilizer.

Treatment	<u>Growth stages</u>							
	R_1^a				R_2^b			
	<u>1993 growing season</u>							
	R^c		I^d		R		I	
	<u>SIM^e</u>	<u>FM^f</u>	<u>SIM</u>	<u>FM</u>	<u>SIM</u>	<u>FM</u>	<u>SIM</u>	<u>FM</u>
Control	0.70	1.07	0.90	2.20	1.40	0.48	1.20	1.80
22 kg P ha ⁻¹	1.40	3.50	1.60	4.00	3.20	3.50	3.50	5.40
88 kg P ha ⁻¹	1.50	3.22	1.80	4.60	3.50	3.22	4.20	5.80
176 kg P ha ⁻¹	1.50	4.25	1.80	3.40	3.50	4.75	4.20	4.90
	<u>1994 growing season</u>							
Control	1.20	1.80	1.30	1.08	1.90	0.48	1.70	1.25
22 kg P ha ⁻¹	1.50	3.20	1.40	3.60	2.40	1.20	3.10	1.25
88 kg P ha ⁻¹	1.50	2.50	1.60	3.10	2.50	1.40	3.50	1.60
176 kg P ha ⁻¹	1.50	2.10	1.60	4.20	2.50	1.50	3.50	1.70

^a R_1 refers to flowering stage

^b R_2 refers to harvest maturity stage

^c R refers to rainfed experiment

^d I refers to irrigated experiment

^e SIM refers to simulated (model predicted) data

^f FM refers to field measured (observed data)

The model better predicted the P uptake from applied TSP than from the MPR fertilizer. Such results may have been influenced by the fact that during the simulation process, the MPR is first placed in the stable P pool, then P moves to the active P pool before it is accounted for the plant P uptake in the labile pool. The three P pools interact directly or indirectly and affect the P uptake by the crop and the effectiveness of fertilizer use. However, the quantitative relationships of the processes involved are poorly understood and it is difficult to apply to such comprehensive crop models (Wolf *et al.*, 1987). The other speculation for such results is that, the MPR characterization conducted at IFDC laboratories (Table 4.1) indicated the Minjingu phosphate rock's complexity of its chemistry due to its different degrees of reactivity. Such rock's characteristics can lead to the discrepancies in results as shown in this study.

The P pools calculated in the model for the 1993 irrigated experiment are shown in Figure 3.2a for the TSP treatments and Figure 3.2b for the MPR treatments along with the simulated plant uptake. The results from the TPS addition demonstrate how the stable pool gradually increases during the season after the fertilizer was added. The active increased rapidly after the fertilizer was added and then began to decrease when the resin pool was at a low value. The resin pool has fertilizer added into it on the date of application. It decreases rapidly, flowing into the active pool. The uptake was independent of the labile concentrations early in the season when all the pools were relatively high, but the uptake declined at different times depending on the level of the labile pool in the root zone. The P uptake patterns of the plants as measured in the experiment generally agree with the results as well as the soil resin P values as estimated by the Bray test.

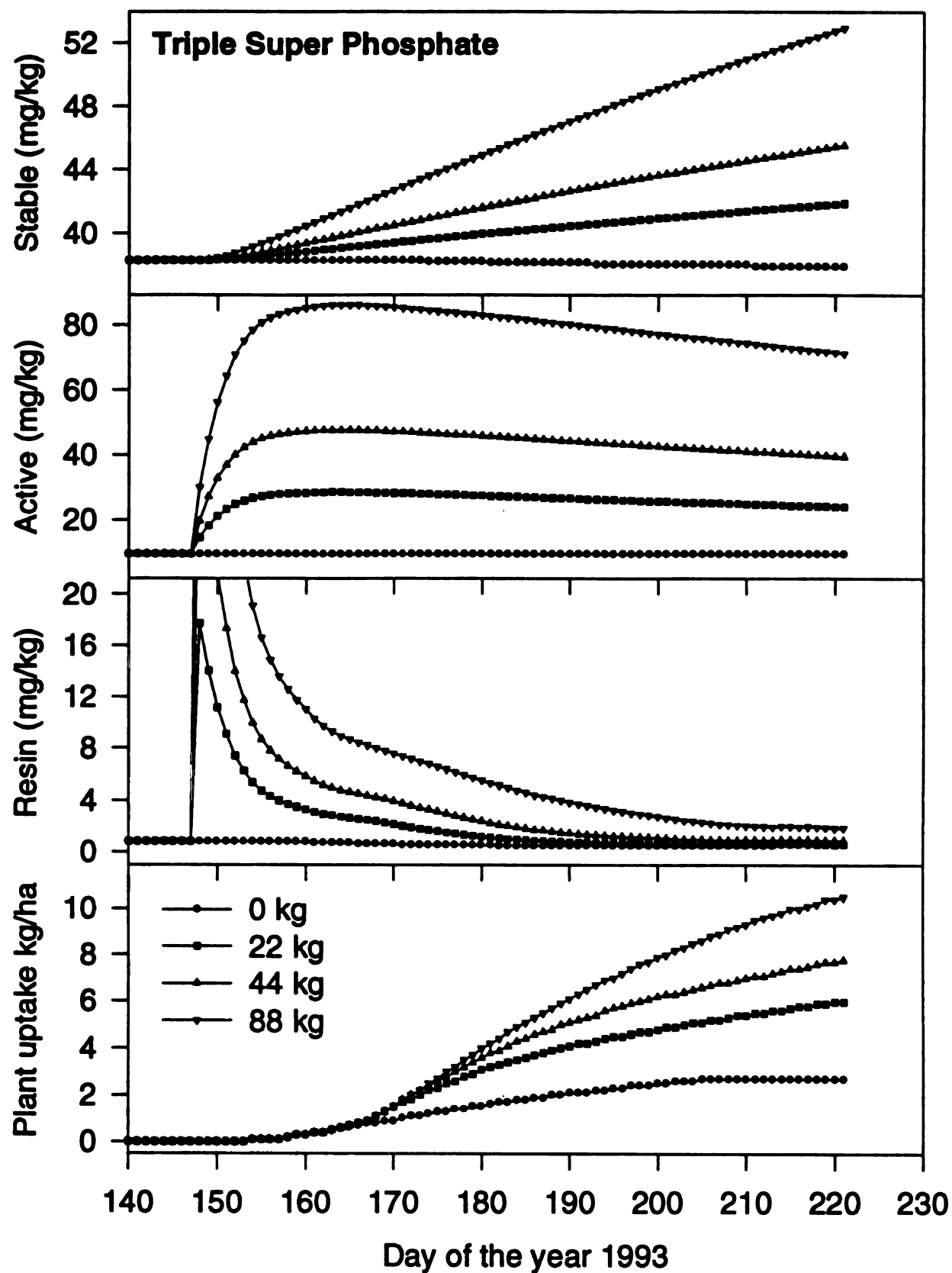


Figure 3.2a. The simulated distribution of the P soil pools and the P plant uptake during the 1993 irrigated experiments for various additions of TPS. The fertilizers were applied on Day 147.

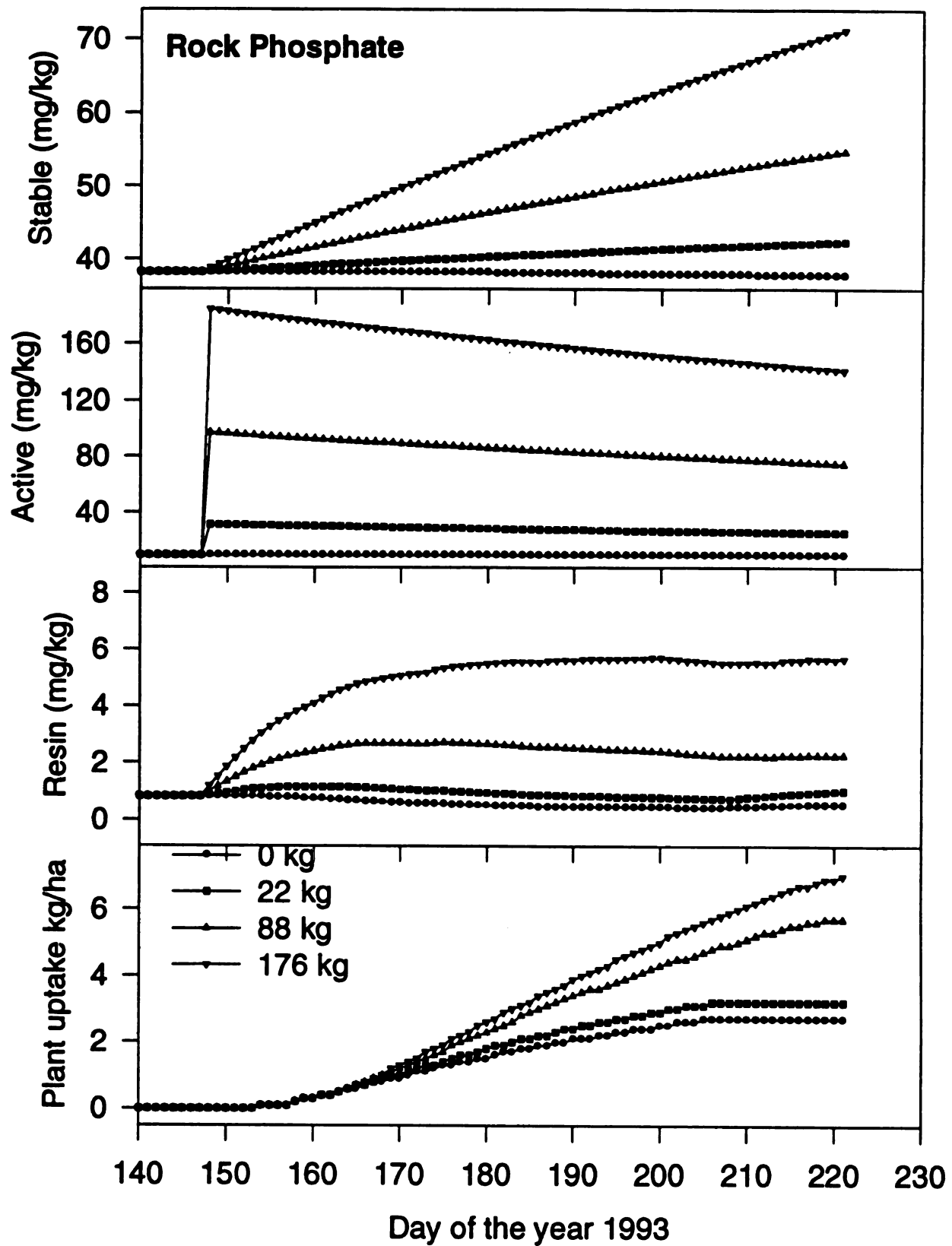


Figure 3.2b. The simulated distribution of the P soil pools and the P plant uptake during the 1993 irrigated experiments for various additions of MPR. The fertilizers were applied on Day 147.

The MPR results indicate the different reactions required for the rock phosphate source to influence the resin pool and the plant uptake. The rock phosphate is added to the active pool at the date of application and then begins to move to the resin pool and the stable pool. The resin pool is considerably lower during the first part of the season as compared to the TPS source because of the time required for the transfer from the active pool to the resin pool. The soil P at the end of the season and the plant P uptake data show general agreement with the experimental findings.

SUMMARY AND CONCLUSIONS

Field measured data indicated that Minjingu phosphate rock (MPR) was not as effective as TSP in supplying available P to the bean crop. Increased P application resulted in increased P concentration all bean plant parts. Phosphorous concentration varied between experiments, treatments, plant parts, and crop age. The absorption of P by the bean crop continued until late in the season, so the applied P fertilizers resulted in dry matter increase almost to the end of the season. Results show that plots which had the highest P concentration did not necessarily give the highest crop yield. This means that although the P concentration in leaf tissues is extensively used as an indicator of P deficiency, there should be other biochemical events which take place in the plant to help the crop cope with the P stress.

The present study results suggest that farmers who harvest green pods between R_5 and R_7 growth stages result in the highest removal of P nutrient from the field. Since the seed contained 27 to 47% P at harvest maturity, it means that if the by-products (crop residues)

are reincorporated in the fields, a substantial amount of P can be recycled for the succeeding crop. This may reduce the mining of plant nutrients from already impoverished soils of Tanzania.

The model predicted quite well the P accumulation in plots treated with TSP during the 1993 season under rainfed and in the 1994 irrigated experiment. However, there were disagreements between predicted and field measured P accumulation values from plots that were applied with the MPR fertilizer. The model was found to be very sensitive to the soil initial P conditions, and model parameters such as RCONST (i.e., rate of movement between active P and stable P pools), FPO_4 (i.e., P fraction used to calculate the P uptake) and RPO_4U (i.e., the plant potential uptake from the soil).

The applied P fertilizers were fairly well used by the bean crop, for at maturity about 5% of the applied P had been taken up by the crop in plots that received high rates of P. Such results agree with those reported in the literature for beans by Thung (1991). The critical P value obtained from irrigated conditions are considered to be appropriate for beans grown at Sokoine University of Agriculture farm.

RECOMMENDATIONS FOR FUTURE RESEARCH

Current literature shows that the vesicular-arbuscular mycorrhizal fungi (VAMF) can increase the P uptake by bean plants (Kucey 1987, Kucey and Janzen 1987, and Kucey *et al.*, 1989). Therefore, investigations to bean responses to VAMF infection on improved P uptake should be initiated in Tanzania. Different bean cultivars have different P uptake efficiencies

(Fageria, 1989; Yan *et al.*, 1995a, b). Therefore, studies on P acquisition mechanisms in bean cultivars for higher P efficiency in Tanzania is recommended.

Efforts should be made to improve the current P model so that accurate simulations of P concentration, accumulation (uptake), and ultimately crop yield can be predicted. Therefore, there is a need to conduct a more detailed studies to determine physical and chemical characteristics of MPR and the soil properties which affect the rock's dissolution. This will enable researchers to improve the theoretical understanding of interactions between plant parameters, soil factors and MPR fertilizer characteristics. Further, this may help in the improvement of the existing P model.

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CHAPTER 4
AGRONOMIC EVALUATION OF MINJINGU PHOSPHATE ROCK (MPR)
USING BEAN (*Phaseolus vulgaris* L.) CROP UNDER
RAINFED AND IRRIGATED CONDITIONS.

ABSTRACT

Phosphorous (P) is critical to improving soil fertility for sustainable agriculture in Tanzania. This study was conducted to assess the growth and yield of a bean crop as influenced by triple superphosphate (TSP) in comparison with Minjingu phosphate rock (MPR) applied as direct applied fertilizer under rainfed and irrigated conditions. The MPR reactivity was determined using the neutral ammonium citrate (NAC) extraction method. Biomass harvests and growth parameters were determined at V₃, R₁, R₃, R₇, and R₉ growth stages. At maturity, total dry matter, seed yield, and yield components were analyzed. Laboratory analysis results with NAC indicated that MPR is highly a reactive phosphate rock (PR) with the value of 6.7% P₂O₅ second extraction. However, the degree of CO substitution for PO₄ in the apatite indicated the rock was only a medium to low reactive PR. Soil pH, extractable P, and exchangeable Ca increased in plots where P fertilizers were applied regardless of the type, and rate of fertilizer used. These increases were higher in plots

that received higher rates of MPR. The crop growth stages, and maturity periods depended mainly on the cool night temperatures during the growth periods, and not on the P treatments. Statistical analyses using Duncan Multiple Range Test ($P=0.05$) showed that TSP and MPR had equal agronomic effectiveness. Additional analysis using orthogonal comparisons between TSP and MPR showed similar results under rainfed conditions. However, under irrigated conditions of 12 comparisons, TSP outperformed MPR four times, and MPR outperformed TSP five times. The relative agronomic effectiveness (RAE) of MPR with respect to TSP (100%), in terms of increasing total dry matter, ranged from 20.66 to 64.59% under fresh P, and 18.15 to 64.15% under annual P. The study also showed that MPR can have liming effects when applied under high rates. The conclusion drawn from this study is that apart from the soil characteristics, such as low soil pH, low P, and low Ca, the use of MPR should be recommended in areas where irrigation can be applied for bean production.

LITERATURE REVIEW

Phosphorous (P) is a key plant nutrient. It is mobile in plants, being redistributed from older to younger parts, but non-mobile in the soil. It is derived from soil organic and inorganic fractions such as orthophosphate; and P-containing minerals such as the apatites of Ca-, Fe-, and Al-phosphates. Also, from the labile pool consisting of P adsorbed on soil colloids and of Fe- and Al-phosphates in equilibrium with P in solution (Mengel and Kirkby, 1987). Phosphorous provides the best example of specifically adsorbed anions in negatively charged soil particles.

Many soils fix large quantities of P by converting readily soluble P to forms less available to plants. Phosphorous forms difficult soluble compounds with Fe^{3+} and Al^{3+} at low pH to give compounds such as strengite $[\text{Fe}(\text{OH})_2\text{H}_2\text{PO}_4]$ and variscite $[\text{Al}(\text{OH})_2\text{H}_2\text{PO}_4]$ (Juo and Ellis, 1968). At higher pH values it forms difficult soluble compounds with Ca^{2+} such as octacalcium phosphate $[\text{Ca}_8\text{H}(\text{PO}_4)_3]$; and hydroxyapatite $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})]$ (Lindsay and Moreno, 1960).

In the field, the application of P to a bean crop results in increased plant growth and seed yield (Manrique, 1986; Lynch *et al.*, 1991; Yan *et al.*, 1995 a and b), radiation use efficiency (RUE) (Manrique, 1993), and pods per plant (Thung, 1991). The enhanced growth of bean plants with P fertilization is brought about by a promotion of metabolic activity (Whiteaker *et al.*, 1976). Similar results are reported on soybean by Howell (1984), and Lauer and Blevins (1989). Applied P has also shown some influence on leaf senescence in soybean (Craft-Brander, 1992a and b). Studies conducted at IFDC have shown that application of P in the form of phosphate rock (PR) does increase the biological nitrogen fixation (BNF) in soybean plants (Chien *et al.*, 1993). Sa and Israel (1995) working with soybean plants, observed that P deficiency impairs N fixation by decrease of hexose and sucrose concentration in nodules, indicating low carbohydrate use. This low carbohydrate use may result in the decreased movement of ureide and other N constituents in the plants. Most of the bean-growing areas in the tropics normally have highly weathered acidic soils, that are low in soil pH (less than 5.0). The soils also have low CEC which is usually less than $10 \text{ cmol (+) kg}^{-1}$, low base saturation, and high aluminum saturation, often above 20%. Although liming is an old agricultural practice, going back 2000 years in agriculture (Barber,

1967), it is still not commonly practiced in Tanzania. This is mainly because the resource-poor farmers in Tanzania cannot afford such a high-input solution.

High "free" Al^{3+} in soil solution can produce phytotoxicity in beans because it is absorbed rapidly and builds up a high concentration of Al in cells. This creates cell disorders by affecting the membrane structure and function, DNA synthesis and mitosis, cell elongation and metabolism (Wright, 1989). Bean cultivars such as "Romano" and "Dade" are resistant to Al phytotoxicity. Studies have shown that the mechanism of Al-tolerance is by exudation of citric acid into the rhizosphere (Miyasaka *et al.*, 1991). Other legumes such as pigeon pea [*Cajanus cajan* (L) Millsp] have been shown to be more efficient in using iron-bound (Fe-P) P than other crop species. This ability is also reported to be on the root exudates, in particular piscidic acid and its *p*-O-methyl derivative, which releases P from Fe-P by chelating Fe^{3+} (Ae *et al.*, 1990).

The reddish Oxisols and Ultisols occur in most parts of Tanzania. Such soils are poor in organic matter, have low pH and crops grown on these soils show significant P deficiency (Uriyo and Kesseba, 1973). To ameliorate P deficiency, fertilizer use is being encouraged by the Tanzanian government. However, the relatively slow growth of fertilizer production in the country compared with fertilizer use, has made the country increasingly dependent on fertilizer imports. As pointed out by Bumb (1993), because of foreign exchange shortages and debt crises, a significant proportion of the fertilizer imported is financed through aid. Although TSP has been the most popular phosphate fertilizer in Tanzania (IFDC, 1990) currently it has become too expensive for most farmers. This is because the only fertilizer plant in the country ceased production in 1991 through defective machinery and lack of spare parts. Thus, all required fertilizer has to be imported (Dr. Surjit Sidhu, IFDC principal

economist, 1995, personal communication). Due to these problems the government has been encouraging the use of locally available PR fertilizers.

Important P deposits in Tanzania are summarized by Mchihiyo (1991), and Mwambete (1991). There are three types of phosphate deposits found in Tanzania: guano, sedimentary, and igneous deposits. Among these, the only significant deposit in the country currently being mined is of the sedimentary type at Minjingu in the Arusha Region (Van Kauwenbergh, 1991). Its deposits are estimated to be 10 million metric tons (Hammond *et al.*, 1986). Samples of Minjingu ore, concentrate, and bird-bone concentrate have been characterized at IFDC (Van Kauwenbergh, 1985; 1991).

The apatites that are found most often in commercial PRs are generally in the form of carbonate fluorapatite (francolite). The francolite is defined as a carbonate containing more than 1% F, and an appreciable amount of CO₃ (Sandell *et al.*, 1939). Based on statistical models, McClellan and Lehr (1969) suggested that the empirical formula for francolite be generalized as:



In MPR, apatite is the major phase ranging from 68 to 88%. The apatite of MPR is complex and unusual (Van Kauwenbergh, 1991).

The key measure that indicates the speed at which the P fertilizer can increase the supply of plant available P ions in the soil solution, in the short term, is its solubility in water. Phosphate forms that are water soluble can be expected to release a large proportion of the P immediately upon wetting, although a significant portion will remain in less soluble forms as in the case of calcium phosphate fertilizers (Lindsay and Stephenson, 1959). An indication of the rate at which a fertilizer can release P is usually given by its solubility in water and/or

NAC, and 2% formic acid (Mullins, 1988; Sale and Mokuwunye, 1993; Mullins *et al.*, 1995).

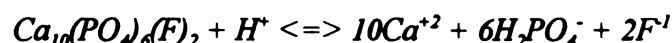
Reactive PRs are those in which some of the phosphate groups in the apatite crystal structure has been substituted by a carbonate group during its formation. In general, the greater the carbonate substitution, the smaller the crystal size, resulting in a more soluble PR. The most reactive PRs are those having a molar PO_4/CO_3 ratio less than 5.0 (Sale and Mokuwunye, 1993). Chien (unpublished report⁴) outlines the effect of CO_3 substitution for PO_4 on chemical reactivity of apatite as due to: (i) The decrease in unit cell *a*-axis that results in a decrease in crystallite size of apatite, (ii) Substitution of planar CO_3^{2-} for tetrahedral PO_4^{3-} causes structure instability that results in an increase in reactivity and, (iii) The resulting highly substituted francolites are less thermodynamically stable than the fluorapatite.

According to the report by Van Kauwenbergh (1991), MPR has a high NAC reactivity ranging from 5.6 to 12.9% P_2O_5 . However, Kpomblekou-A and Tabatabai (1994), reported of MPR having medium NAC reactivity of 1.49-1.77% P_2O_5 . Such contradicting results indicate how unusual and complex MPR is.

There are a number of phosphate rock's, environmental, management and plant factors that influence the agronomic effectiveness of directly applied PRs (Sale and Mokuwunye, 1993; Allen *et al.*, 1995). Phosphate rocks must be finely ground to obtain a sufficiently rapid dissolution rate. Fine grinding increases the particle surface areas of PRs that are exposed to the soil. This increases the potential dissolution rate (Wilson and Ellis, 1984; Sale, 1989; Le Mare, 1991), but fine grinding is not a substitute for reactivity.

⁴S.H. Chien, 1995. Chemical mineral, and solubility characteristics of phosphate rock for direct applicaiton. International Training Workshop on Direct Application of Phosphate Rock and Appropriate Technology Fertilizers in Asia: What Hinders Acceptance and Growth. Kandy, Sri Lanka. February 20-14, 1995. IFDC, P.O. Box 2040, Muscle Shoals, AL 35660.

Reducing PR particles to a size less than 150 microns by grinding is generally not warranted as fine particles do not increase effectiveness greatly (Khasawneh and Doll, 1978). MPR concentrate is produced at 70% passing a 75 - micron screen, thus further grinding is not needed for direct application (Van Kauwenbergh, 1985; 1991). Soil properties where the PRs are directly applied do affect the rock's effectiveness. The dissolution process of PRs may be described as:



Thus, soil conditions that favor the dissolution of the PR are those which enable the products of dissolution, the Ca^{2+} , $H_2PO_4^-$ and F^- ions, to rapidly diffuse away from the surface of the dissolving PR particle. This drives the reaction to the right in favor of PR dissolution (Wilson and Ellis, 1984; Sale, 1989; Sale and Mokuwunye, 1993). In general terms, PR dissolution in soil solution is favored when the soil pH, soil exchangeable Ca, and soil solution P concentration are low (Khasawneh and Doll, 1978; Le Mare, 1991; and Chien, unpublished report⁵). As the P sorption capacity increases, the dissolution rates of the PRs placed in those soils also increase (Smyth and Sanchez, 1982; Syers and Mackay, 1986). This is due to the removal of phosphate ions from the soil solution by rapid sorption on Fe and Al compounds.

The other important soil factor in PR dissolution is soil organic matter. Organic matter forms complexes with soil Ca^{2+} and those released from PR dissolution, thereby diminishing Ca^{2+} ion concentration in the soil solution and enhancing dissolution of the PR applied (Chien

⁵Chien, S.H. 1990. Reactions of phosphate rocks with acid soils of humid tropics. Workshop on Phosphate Sources for Acid Soils of Humid Tropics of Asia. Kuala Lumpur, Malaysia. Nov. 6-7, 1990. International Fertilizer Development Center, P.O. 2040, Muscle Shoals, AL 35660.

et al., 1990; Le Mare, 1991). Hence, PRs tend to be more effective in acid soils containing high amounts of organic matter than in soils where the organic matter content is low (Le Mare, 1991). In general terms, no single soil characteristic appears to have a consistent and predominant influence on P release from PRs (Anderson *et al.*, 1985).

Fertilizer efficiency of PRs increases with increasing rainfall, and the response to PR is more erratic under low-rainfall conditions (Hammond *et al.*, 1986). Films of moisture surrounding the PR particle enable the products of dissolution, the Ca^{2+} , H_2PO_4^- and F^- ions, to diffuse away from the dissolving surface of the particle. Adequate levels of soil moisture also enable the plants to have well-developed roots that are suited to using the P from the PRs (Hammond *et al.*, 1986). Temperature has been found to have no significant effect on the dissolution of PR in the soil. This implies that the influence of temperature on the agronomic effectiveness of finely ground PR is most likely an indirect result of the influence of temperature (climate) on the rate of physiological development of the crop (Hammond *et al.*, 1986; Sale, 1989).

The application method of PR fertilizer has a marked impact on its effectiveness. Applying the PRs in a concentrated band results in a reduction in the dissolution rate of the fertilizer due to the increase in levels of Ca^{2+} and F^- ions around the dissolving particles (Hughes and Gilkes, 1986; Sale, 1989). Thus, for a PR to be most effective it should be broadcast on the soil surface and incorporated into the soil at the time of planting (Sale, 1989; Chien *et al.*, 1990 b; Sale and Mokuwunye, 1993). The use of lime reduces PRs dissolution rates because liming reduces the H^+ and increases the Ca^{2+} in the soil solution. To overcome this problem, Foth and Ellis (1988) recommend applying PR about six months in advance of

lime. This would allow significant amounts of PR to dissolve before the pH and the calcium status of the soil are raised by lime application (Sanchez and Salinas, 1981).

Differences among crops in their utilization of PRs depend on their requirements for both P and Ca, and on how the uptake of these elements affects the composition of the rhizosphere. Crops that take up large amounts of Ca to lessen the ambient concentration in the soil enhance the dissolution of PRs (Le Mare, 1991). Crops with extensive root systems, such as cassava (*Manihot esculenta* Crantz) which is commonly grown in acid soils in the tropics, are infected with hyphae of vesicular-arbuscular mycorrhizae (VAM), which helps the transfer of P from poorly soluble well distributed sources to plants, thus increasing the P from the PRs (Le Mare, 1991; O'Keefe and Sylvia, 1991). In leguminous plants, there is usually an acidification of the rhizosphere which results in an increase on the effect on PR dissolution (Kirk and Nye, 1986). This is usually due to H-ions that build up in the rhizosphere around root surfaces, which results from the excess uptake of cations by the legume plant roots (Bekele *et al.*, 1983). Such effects occur due to legume plants active nitrogen fixation process (Bolan and Hedley, 1991). In general terms, crops do vary in their ability to utilize the PRs and these differences contribute to their relative agronomic effectiveness.

Some PRs are not suitable for direct application because of their low chemical reactivity (Hammond *et al.*, 1986). Therefore, partial acidulation of such PRs may improve the agronomic value at a lower cost than would be required to manufacture the conventional, fully acidulated fertilizers from that same PR (Hammond *et al.*, 1986; Chien and Hammond, 1988). Acidulation of low quality PRs does release metallic impurities such as Fe, Al, K, and Mg which react to form precipitates in the final fertilizer product (Mullins, 1988). In some

studies, agronomic effectiveness of partially acidulated phosphate rocks (PAPR) has been shown to be as good as, or better than, that of water soluble P fertilizer such as TSP on soils with high P-retention capacity (McLean and Wheeler, 1964; McLean and Logan, 1970; Chien and Hammond, 1989).

Few studies have been conducted in Tanzania using MPR on beans as a test crop. Chesworth *et al.* (1988) compared the effects of the MPR and TSP yields of bean crops grown on a plots with Ultisols soils. Although the soil tested low in pH (4.6) and low P (5.6 ppm), there was no significant response. These results were attributed to considerable amounts of exchangeable Al found below 15 cm soil depth (Al saturation values >50%). Similar results were reported by Giller *et al.* (1988), and Smithson *et al.* (1990), and were attributed to the deficiency of K in the soil. Such conclusions show how poor performance of MPR in comparison to soluble P fertilizers has mostly been attributed to reasons other than the rock's characteristics.

In addition, most of the studies reported on the evaluation of MPR in Tanzania using various crops were conducted at a single application rate. Where several application rates were used, the seasons in which MPR was applied were different. Further, all field studies have been conducted only under rainfed conditions. Conclusions from such studies make proper evaluation of MPR as a direct applied fertilizer difficult. Since most studies have been inconsistent, the main purpose of part of this study was to: (i) To assess the growth and yield of bean crop as influenced by MPR in comparison with TSP fertilizer, and (ii) also to assess the agronomic effectiveness of MPR as a direct applied fertilizer under rainfed, and irrigated conditions.

MATERIALS AND METHODS

The experiments were conducted at Sokoine University of Agriculture, in the Morogoro Region during the 1993 and the 1994 growing seasons. Details on location, altitude, meteorological variables, soil characteristics, and experimental procedures are fully described in Chapter 2. The MPR chemical characteristics were determined at IFDC laboratories (Table 4.1). Pre-plant soil characteristics were taken seven days before planting in the 1993 growing season (Table 2.1), and 365 days after the treatments' application in the 1994 growing season (Table 4.2a). Post-harvest soil characteristics were taken seven days after harvest in both seasons (Tables 4.2b). Soil extractable P at all sampling times, including those at post-harvest times, was analyzed by using the Bray-I method as suggested by Chien (1978), and Chien *et al.* (1987). Soil sampling was done for all treatments, but not in all experimental plots. Therefore, soil chemical characteristics determined were not statistically analyzed.

Block A was used to assess the influence of fresh applied P on growth, and yield of bean during the 1993 growing season in both experiments. In the following season, block A was used to assess the influence of residual P (refer to Chapter 5 for details). Fresh applied P in this study refers to P fertilizer applied at sowing in plots that had not received P in the previous season. Although block B was used to collect data for evaluating the BEANGRO crop model (as described in Chapter 2), this block was also used to assess the influence of annual applied P on bean crop performance. Annual applied P as used in this study refers to P fertilizer applied at sowing in each season for two or more successive seasons.

Plant heights (cm) were measured at R_4 growth stage in each experiment by taking the average heights of 10 randomly picked plants per plot from the two central rows. Crop growth rate (CGR) between different harvest times for each treatment were calculated as described by Radford (1967). Maximum CGR values were recorded in all experiments for both seasons. Harvest index (HI) was calculated from marketable dry bean seed weight as percentage of total dry matter per plot.

At final harvest, 10 plants were picked randomly from each plot and used to calculate the average number of pods per plant (N_p). A subsample of 20 pods was used to determine the number of seeds per pod (N_s) as well as seed weight (W_s). Seed weight (mg seed^{-1}) was calculated by taking the average weight of a hundred seeds. The total seed weight (g) per plant (Y) was obtained by multiplying the number of pods per plant by the number of seeds per pod by the weight of individual seed (mg) i.e., ($Y = N_p * N_s * W_s$). Seed yield per plot was determined after removing all the defective seeds and adjusting to a uniform level of 14% moisture content.

Data were analyzed using MSTAT-C (Michigan State Univ., 1993) statistical program. Data from the two growing seasons showed highly significant ($P=0.05$) season X interaction for all variables. Experiments were analyzed separately for each season. Duncan's Multiple Range Test (DMRT) was used to compare seven treatment means. Since there were no clear differences between TSP and MPR fertilizer levels using the DMRT, additional statistical analyses using orthogonal comparisons between TSP and MPR in agronomic effectiveness were performed. Orthogonal comparison is more powerful than DMRT in detecting differences between two treatments.

To describe the non-linear relationship between total dry matter yield, and rate of P applied from MPR and TSP sources, a semilog function was used as described by Chien *et al.* (1990).

$$y_i = Y_0 + \beta_i \ln X, X > 1$$

where

Y_i = Yield obtained with source (i),

Y_0 = Yield obtained with no P application (common to all P sources),

β_i = Regression coefficient of source (i),

X = Rate of P applied,

To evaluate the RAE of the MPR source with respect to TSP, the RAE was defined as the ratio of two slopes,

$$RAE \text{ index}(\%) = \frac{b_{MPR}}{b_{TSP}} \times 100.$$

To compare treatment effects among P sources, the standard errors (SE) of estimate for b_i were used to evaluate whether a given P source was statistically different from the other source in terms of increasing total dry matter production. This method has been used by Hellums *et al.* (1989) to compare the agronomic effectiveness of various PRs with respect to CaCO_3 , and by Chien *et al.* (1993) to compare the RAE of various PRs with respect to TSP in soybean.

RESULTS AND DISCUSSION

General Observations

The experimental sites contained low pH, low extractable P, and low exchangeable Ca. At both experimental sites the initial soil N, P, Ca, K, Mg, and Al saturation were below the critical levels for bean production suggested by CIAT (Flor and Thung, 1989). The high BD of 1.35- 1.55 g cm⁻³ at the experimental sites (Tables 2a and 2b) may have affected root penetration, and therefore resulted in growth and yield reduction in the bean crop (Asady *et al.*, 1985).

Most of the plants were nodulated in both experiments, but did not have a large mass of pinkish nodular tissues. At emergence plant population was >90%, but at harvest it was reduced to as low as 65% in some plots due to beanfly (*Ophiomyia* spp) and termite (*Microcerotermes* spp) and rodent attack (Appendices 5a and b). Nutsedges (*Cyperous rotundus* and *C. esculentus*) were the most important weed species at the irrigated site. At the rainfed site, wondering jew (*Commelina benghalensis*), and wild spinach (*Amaranthus* spp) were the dominant weed species. Due to high seed infection by ascochyta blight, the infected seed were removed. Therefore comparison of the TSP and MPR fertilizer effect on bean performance are discussed using only the TDM production values in this chapter.

Minjingu Phosphate Rock Characteristics.

Table 4.1 indicates some of the selected chemical characteristics of the MPR ore used during this study. The length of the axis was found to be 9.3586 +/- 0.006 angstroms (unit cell a-dimension).

The soluble P results indicate the rock is highly-reactive. However, the degree of CO₃ substitution for PO₄ in the apatite structure indicates the rock is only a medium to low PR. Similar results were reported by Van Kauwenbergh (1991), and Kpomblekou-A and Tabatabai (1994). This suggests that non-apatitic P minerals such as Fe-Al-P, which are more soluble than apatite in NAC may be present. Further, the MPR may contain a small fraction of hydroxyapatite that is more soluble than the francolite. This small amount of hydroxyapatite may not affect x-ray diffraction peaks, but affects the solubility measurements (Dr. S.H. Chien, 1995 personal communication).

Table 4.1. Selected properties of Minjingu phosphate rock *

Empirical formula $\text{Ca}_{9.86}\text{Na}_{0.10}\text{Mg}_{0.04}(\text{PO}_4)_{5.58}(\text{CO}_3)_{0.42}\text{F}_{2.1}$	
Selected properties	Value
pH	9.0
Total (P%)	13.5
Reactivities (% P_2O_5)	
Neutral ammonium citrate (NAC)	
First extraction	5.3
Second extraction	6.7
*Determined at the International Fertilizer Development Center (IFDC) AL, laboratories.	

Effect of P Treatments on Soil pH, Extractable

Phosphorous and Exchangeable Calcium.

At harvest of the 1993 experiment, the soil pH, Bray-I P (ppm), and exchangeable Ca (meq 100g⁻¹ soil) in plots that received P had increased (Table 4.2b) in comparison with the values at pre-planting time, i.e., before the initiation of the experiment during the 1993 growing season (Table 2.1). The increases observed were higher with high rates of MPR than with TSP applications. The change in soil pH due to the P fertilizer application was higher in irrigated plots than in rainfed. Significant soil pH increases were registered at the end of the 1994 season especially in plots which had received high rates of MPR application compared to the results indicated in Table 4.2a. At the rainfed site soil remained more acidic during the crop growing period. Such conditions may have enhanced MPR dissolution. The

present results show that with time, the applied P fertilizers were releasing more Ca (and probably Mg) thus raising the soil pH. At the end of the 1993 growing season, increases in extractable P were observed in plots which had received fertilizer treatments. Phosphorous increases in plots which received no fertilizer, and those which received TSP may be due to mineralization of organic matter incorporated into the soil during land preparation.

Observations reported here are similar to those reported by Chien *et al.* (1987) who worked with a number of PRs in a Colombian Oxisol with pasture grass (*Brachiaria decumbes*), and Casanova and Solorzano (1994) working with sorghum and soybean on acid soils using TSP and different PRs in Venezuela.

The effects of increase in soil Ca by application of the increasing PR rates has also been observed by Hellums *et al.* (1989) in a greenhouse study, where an increase in Ca uptake by the maize plants, and in the soil exchangeable Ca with the application of higher rates of the PRs obtained from South America and West Africa were reported.

Table 4.2a: Soil pH, Bray-I P and calcium levels in pre-plant soil at of 0-12 cm layer in blocks A and B at the beginning of 1994 growing season.

Treatment	Soil pH	Bray I (ppm)	Ca (meq)
Rainfed experiment			
0 kg P ha ⁻¹	4.47	1.21	2.13
22 kg P ha ⁻¹ TSP	4.56	3.87	2.92
22 kg P ha ⁻¹ MPR	4.61	6.89	3.96
44 kg P ha ⁻¹ TSP	4.49	5.45	3.86
88 kg P ha ⁻¹ TSP	4.58	9.35	4.61
88 kg P ha ⁻¹ MPR	4.44	10.65	5.01
176 kg P ha ⁻¹ MPR	4.48	11.36	6.94
Irrigated experiment			
0 kg P ha ⁻¹	5.51	2.53	2.82
22 kg P ha ⁻¹ TSP	5.41	4.91	4.94
22 kg P ha ⁻¹ MPR	5.83	5.61	5.77
44 kg P ha ⁻¹ TSP	5.42	5.95	4.19
88 kg P ha ⁻¹ TSP	5.66	7.31	4.54
88 kg P ha ⁻¹ MPR	6.81	8.66	6.19
176 kg P ha ⁻¹ MPR	6.11	12.42	7.19

Table 4.2b. Soil pH, Bray-I, and calcium levels in post-harvest soil at 0-12 cm layer in blocks A and B at the end of the 1993 and block B at the end of 1994 growing seasons.

Treatment	Soil pH		Bray I (ppm)		Ca (meq)	
Rainfed experiment						
	<i>A</i>	<i>B</i>	<i>A</i>	<i>B</i>	<i>A</i>	<i>B</i>
0 kg P ha ⁻¹	4.14	4.67	1.63	1.98	2.47	2.01
22 kk P ha ⁻¹ TSP	4.53	4.56	3.33	3.97	2.49	4.91
22 kg P ha ⁻¹ MPR	4.38	4.63	3.51	4.06	3.49	4.78
44 kg P ha ⁻¹ TSP	4.59	4.72	5.75	6.01	3.24	4.86
88 kg P ha ⁻¹ TSP	4.79	4.75	6.96	6.32	3.12	5.32
88 kg P ha ⁻¹ MPR	4.71	4.78	8.94	9.26	3.87	3.19
176 kg P ha ⁻¹ MPR	4.65	4.76	9.19	9.82	4.36	6.27
Irrigated experiment						
0 kg P ha ⁻¹	5.32	5.32	2.31	1.64	2.38	2.51
22 kk P ha ⁻¹ TSP	5.62	5.40	5.35	3.39	2.89	4.98
22 kg P ha ⁻¹ MPR	5.65	5.69	4.86	4.41	2.94	3.04
44 kg P ha ⁻¹ TSP	5.77	5.82	6.79	5.29	2.78	3.18
88 kg P ha ⁻¹ TSP	5.83	5.99	6.94	8.62	2.81	4.81
88 kg P ha ⁻¹ MPR	5.74	6.24	7.16	6.44	2.61	5.96
176 kg P ha ⁻¹ MPR	5.80	6.11	9.94	8.21	3.27	6.46

A represents values from blocks A and B in the 1993 season.

B represents values from block B in the 1994 season.

The higher increase in soil pH, and exchangeable Ca reported in this study due to the application of MPR, is associated with fertilizer characteristics of high pH (9.0) because of the high Ca content (29.2%) in the apatite (Kpombrekou-A and Tabatabai, 1994). Increase of Ca by TSP application was due to its high Ca content of 13.8% (Young *et al.*, 1985). Further, the reaction of free Fe and Al (abundant in the soil) with P ions from the fertilizer, can result in the increase in soil pH (Coleman and Thomas, 1967). The Bray-I P increase was mainly due to the high concentration of total P (15%) in the MPR (Kpombrekou-A and Tabatabai, 1994), and the interaction of the fertilizer with the initial low (1.18-2.83 ppm) soil P. Therefore, the soil characteristics (low pH, low P and low Ca) may have contributed to the observed results in plots that received MPR treatments as indicated by Khasamneh and Doll (1978); Le Mare, (1991), and Sale and Mokuwunye (1993).

Crop Growth, Total Dry Matter and Seed Yield Components as Influenced by Different P Regimes

Figures 4.1 and 4.2 illustrate total dry weights at five growth stages of bean crop grown under different P regimes. The initial crop growth was slow, especially between V_2 and V_3 growth stages. This slow growth may be due to a small number of cells that were dividing, and small leaf area available for sunlight interception and photosynthesis. During this growth stage a large percentage of carbohydrates were being partitioned to the roots (Brown, 1984). With time, total dry weights increased mainly due to an increase in dry weights of stems and pods. The decline in total dry weight was after R_7 growth stage. At this growth stage, leaf and petiole fall from the plants increased. This occurred because at R_4

growth stage carbohydrates, and sugars produced were being translocated to the young pods that were formed. Studies with sorghum have shown that unless adequate nutrients are available during seed formation, this translocation may cause deficiencies in leaves, and premature leaf loss which reduces leaf area duration, and reduces yield (Vanderlip, 1972).

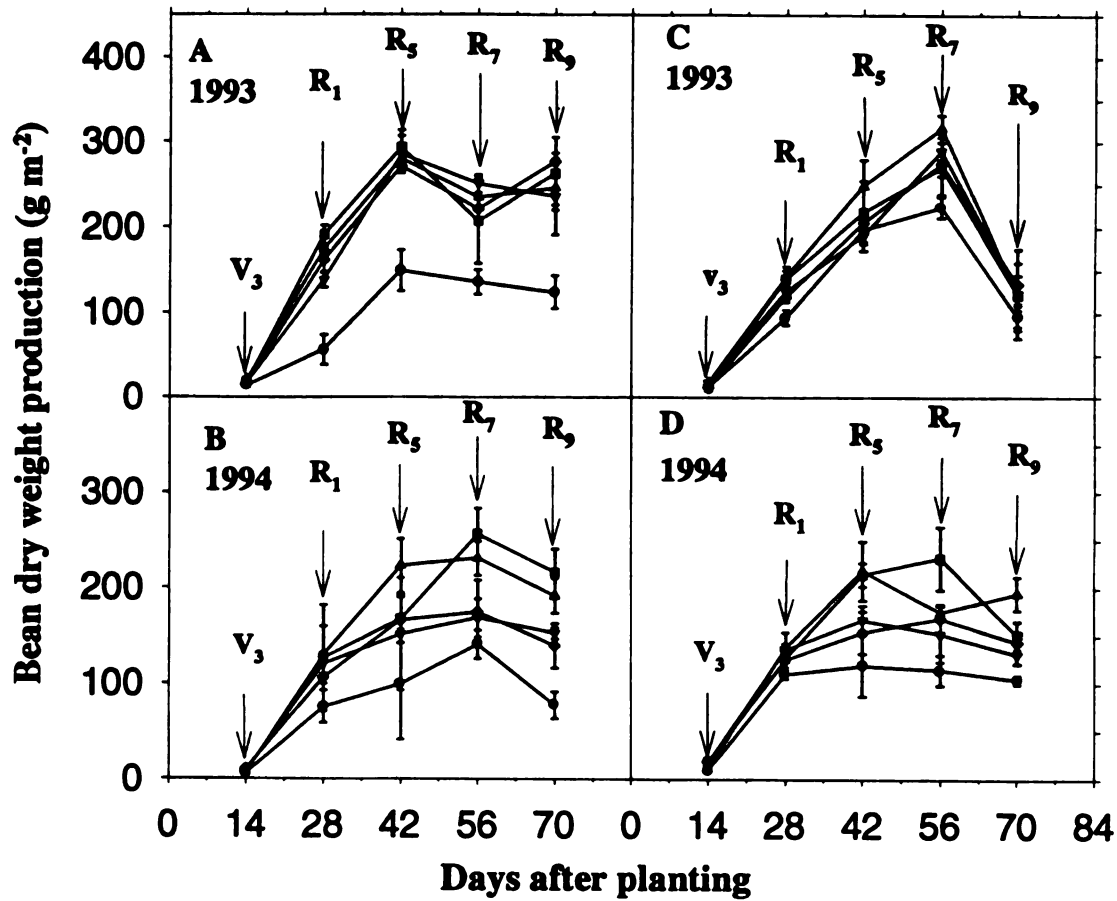
As observed by Saito and Kato (1994) in soybean, and by Acosta-Gallegos and White (1995) in beans, the duration within the growth stage in this study depended mainly on the temperature during the growth period, and not on the fertilizer treatments. Although the rainfed experiments received total precipitation of 475.0 for the 1993, and 341.4 mm for the 1994 season, water stress occurred for about 14 days during the grain filling periods starting at R_4 growth stage. This was more distinct during the 1994 growing season (Figure 2.3 and Appendix 2.b). For the rainfed experiment, total dry matter was lowest in the experiment grown under fresh applied P in the 1994 season, giving the maximum TDM of 202 g m^{-2} . This low yield among all treatments was mainly due to poor rainfall distribution in the period which coincided with the crop reproductive phase.

Canadian Wonder cultivar is a large seeded cultivar (Andean type I), therefore high temperatures during the reproductive phase (Figure 2.1) may have resulted in low rates of canopy photosynthesis due to low leaf N as postulated by Sexton *et al.* (1994). Due to a better rainfall pattern, the 1993 season rainfed experiment with fresh applied P resulted in high TDM production of 302 g m^{-2} (Figure 4.2).

The 1993 irrigated experiment started with a high level of water supply to assure rapid and complete development of the crop root system during the early growth. This was necessary since the experiment was sown at the end of the rainy season when the soil moisture content was already very low, i.e., 15.23% (Table 2.1). Day of the year (date), water applied,

and crop growth stage at which irrigation was applied in both seasons are shown in Appendices 4a and 4b. The amount of irrigation for the 1993 and that of the 1994 growing season differed by 39% because the 1993 crop received a total of 539.0 mm while that of 1994 received a total of 327.0 mm. This difference was due to planting dates, and water deficits during the growing seasons. The 1993 experiment was planted in late May (on 93148) while the 1994 experiment was planted in early May (on 94126) when the soil was still moist (>70% soil available water), and precipitation was still high. While irrigation was applied throughout the growing season of 1993, it was necessary only between 14 and 56 DAP during the 1994 growing season.

Leaf number ranged between 6.00 and 7.33 at the main stem per plant. Leaf production stopped when plants were at the R_3 growth stage as there was no new node production on the main stems at this growth stage. Patterns of treatment effects on leaf production were inconsistent between experiments. In general, the irrigated experiments had a higher number of leaves on the main stem than rainfed experiments. Differences in plant height due to treatments applied were obvious at the R_4 growth stage. The control plots had the shortest plants.



- Control
- 44 kg P ha⁻¹ TSP
- ▲ 88 kg P ha⁻¹ TSP
- ▼ 88 kg P ha⁻¹ MPR
- ◆ 176 kg P ha⁻¹ MPR

Figure 4.1. Bean dry weight production for the crop grown under (A and B) rainfed and (C and D) irrigated conditions with fresh applied fertilizer P. Arrows indicate crop growth stages, and vertical bars represent standard errors (S.E.).

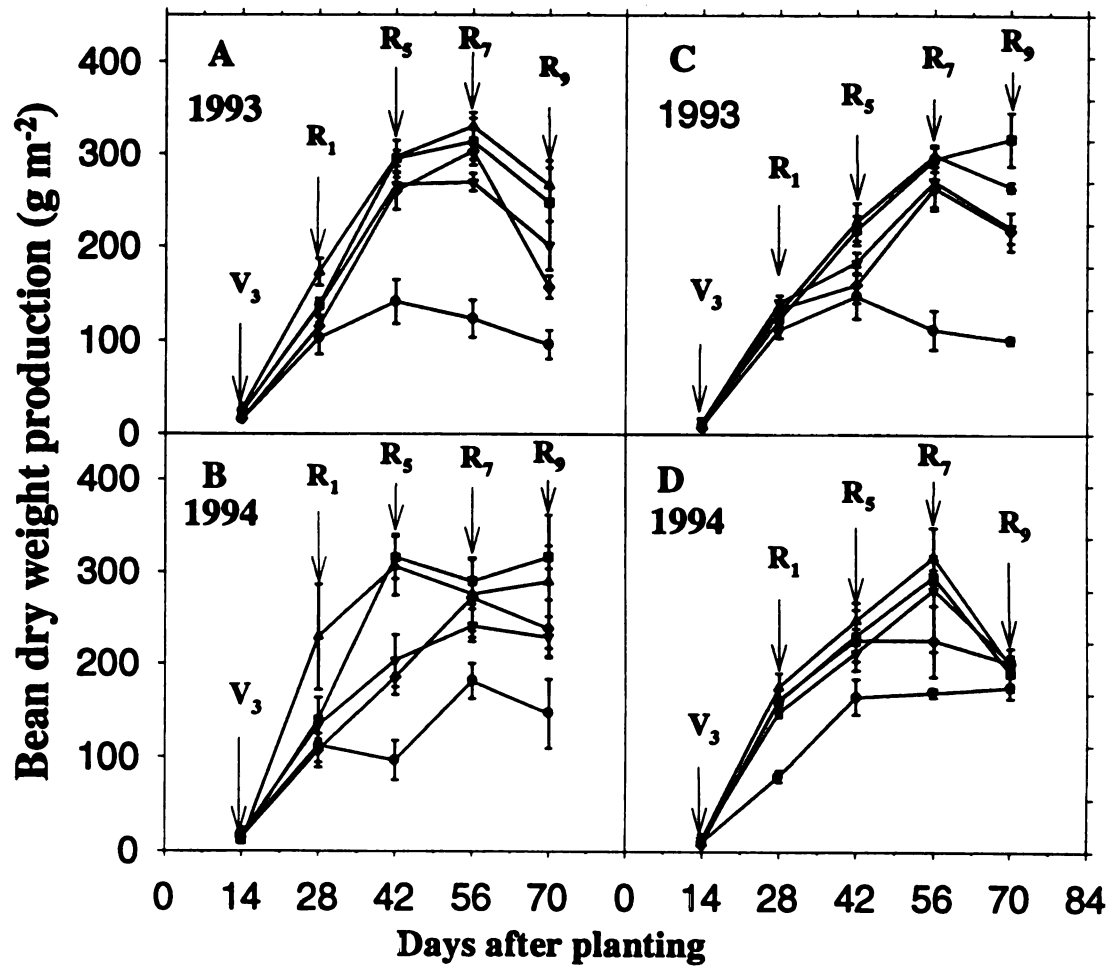


Figure 4.2. Bean dry weight production for crop grown under (A and B) rainfed and (C and D) irrigated conditions with annual applied P fertilizer. Arrows indicate crop growth stages, and vertical bars represent standard errors (S.E.).

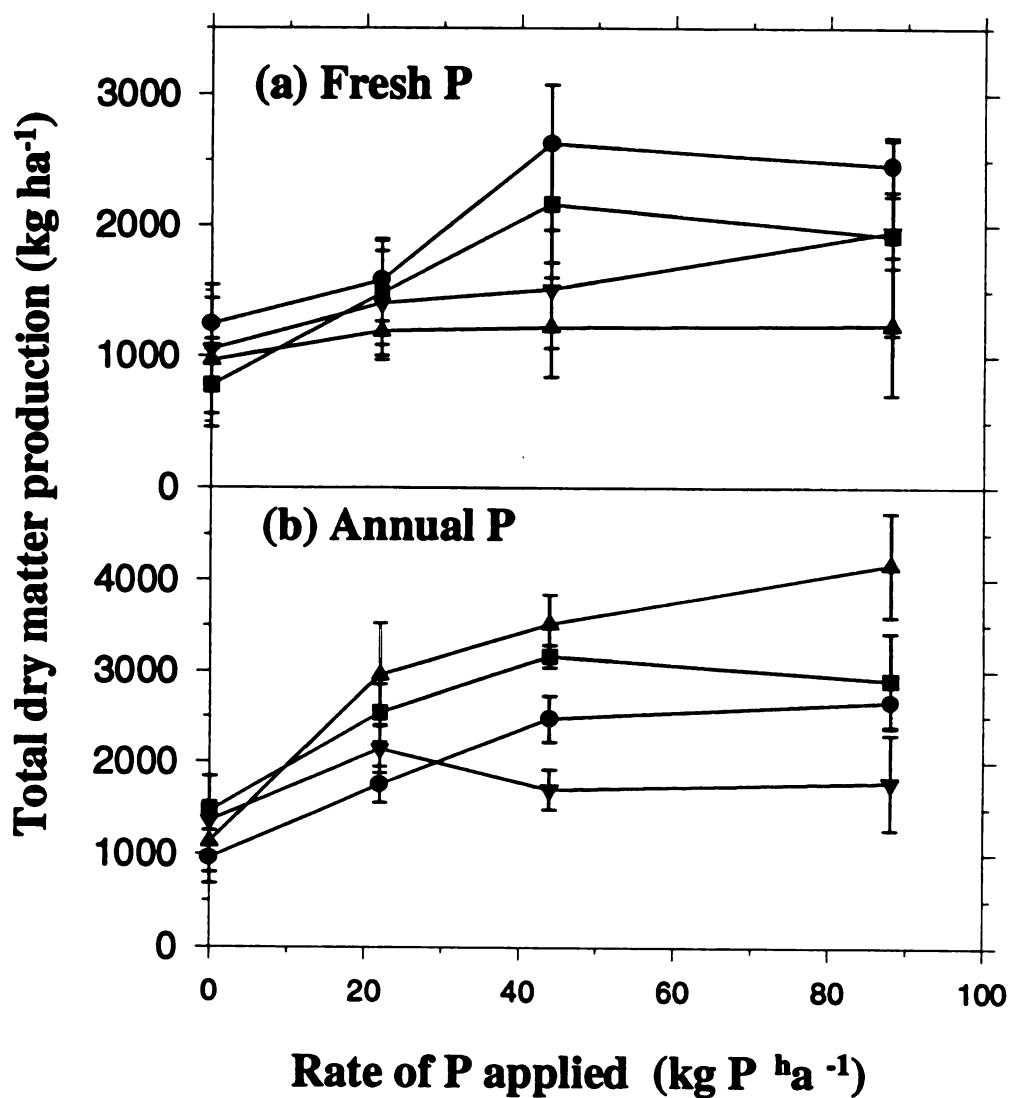
The LAI increased with crop growth at all P fertilizer levels and sources regardless of the fertilizer regimes. Overall, the LAI was maximum at the R_3 growth stage. Application of 88 kg P ha^{-1} (TSP) resulted in the highest LAI values and as expected, the control plots had the lowest values in both seasons. Similar results have been reported in soybean where leaf senescence was decreased by P application due to increase in leaf area duration (LAD) (Grabau *et al.*, 1986).

Gardner *et al.* (1985) pointed out that for a C_3 -plant such as bean, the appropriate CGR value is about $20 \text{ g m}^{-2} \text{ day}^{-1}$. The CGR values ranged from $6.21 \text{ g m}^{-2} \text{ day}^{-1}$ in control plots of the rainfed experiment with a fresh P fertilizer regime, to $15.65 \text{ g m}^{-2} \text{ day}^{-1}$ in plots that received 88 kg P ha^{-1} TSP in the rainfed experiments with an annual P fertilizer regime. The CGR values increased to a maximum between the early and mid-pod filling formation growth stages, and declined thereafter. Therefore, maximum CGR values coincided with mid-pod filling period. During this period the crop was mature enough to exploit most of the environmental factors such as moisture, nutrients, solar radiation, and temperature. Maximum CGR value of $15.65 \text{ g m}^{-2} \text{ day}^{-1}$ (or $156.5 \text{ kg ha}^{-1} \text{ day}^{-1}$) was obtained at the LAI of 2.65. The CGR values of this study suggest that the crop did not have a favorable environment for maximum growth.

Due to the soil and MPR characteristics, and crop management, significant differences were not evident among most treatments for both the CGR and the TDM production during the seasons. At harvest, the TDM production was highest in plots with highest plant population. Total dry matter production is a function of environmental factors, cultivar and crop management. Response to TSP was relatively consistent, and highly significant in both seasons. Under irrigated conditions, application of 88 kg P ha^{-1} (TSP) resulted in the highest

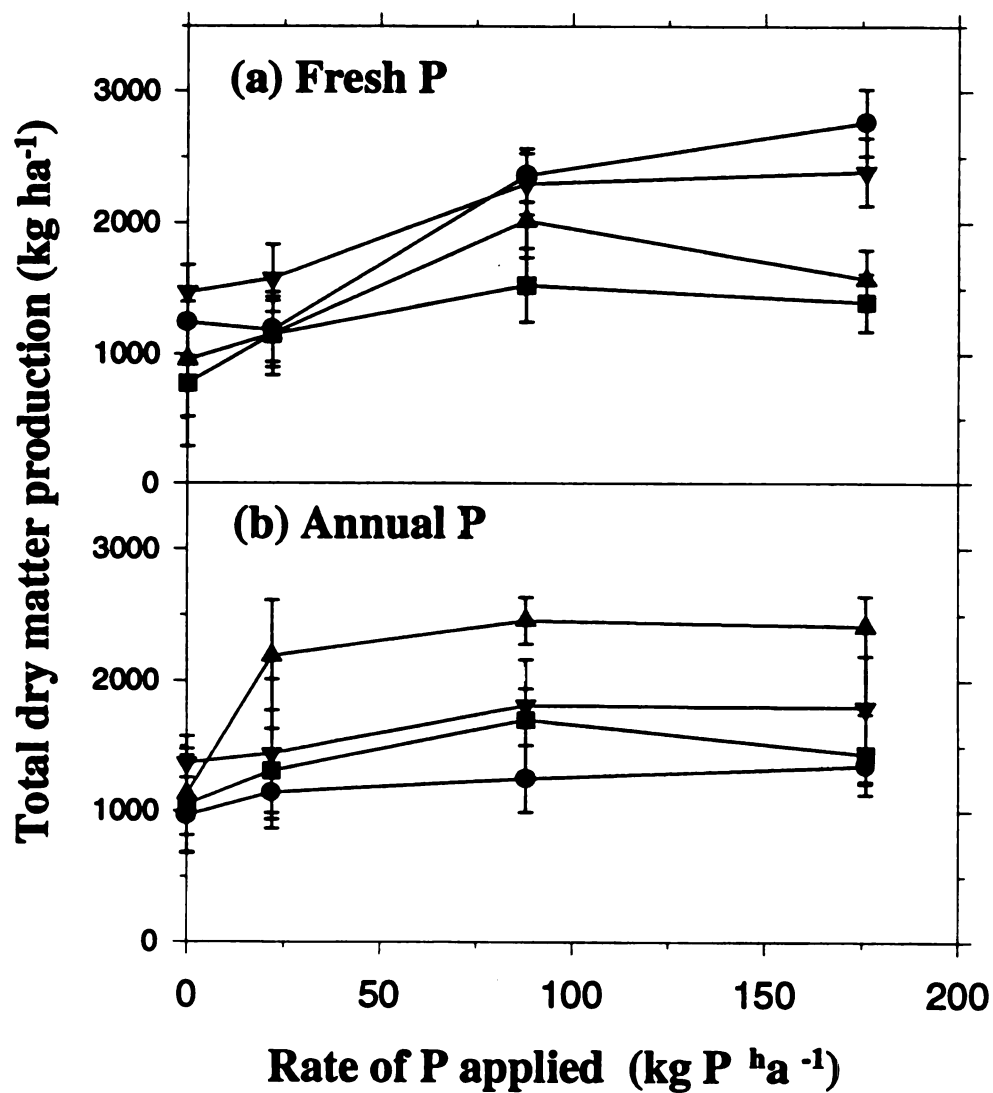
production of TDM (4.2 t ha^{-1}) as shown in Figure 4.3. Bean response to MPR was sporadic, inconsistent, and unexplainable (Figure 4.4). In 1993, MPR had the highest yield under rainfed conditions. However, in the following year, response was the lowest. Such results have led to improper conclusions (IFDC, 1990), and recommendations on the use of MPR in Tanzania. The control plots had the lowest TDM values due to the decrease in crop growth. Such results may have been due to P deficiency in bean plants as indicated in the literature (Yan *et al.*, 1995 a and 1995 b). High levels of applied P may have increased TDM through processes which resulted into higher efficiency in photosynthesis (Lauer *et al.*, 1989), and increased in leaf area (Fredeen *et al.*, 1989).

Since bean is an annual crop, it requires P in early periods of its growth (Fredeen *et al.*, 1989). This is supported by the fact that, the TSP fertilizer which has a higher water solubility (>85%) than the water insoluble MPR supplied relatively the low P at V_3 , and R_1 growth stages (Table 3.2) required by the crop which resulted in higher TDM production. Low response of bean crop to MPR may have been due to the low availability of P from the fertilizer. This may have been caused by factors such as, soil texture at the experimental sites (Table 2.1). Sandy soils such as those found at the sites used for this study are known to accumulate P (Ritchie and Weaver, 1993). This is because sandy soils have low CEC (which is also closely related to soil texture), and do not provide a sink for Ca ions released from PR. Hence, the PR dissolution is slowed which may result in reduced in agronomic effectiveness (Khasawneh and Doll, 1978; Kanabo and Gilkes, 1988).



- TDM rainfed 1993
- TDM rainfed 1994
- ▲ TDM irrigated 1993
- ▼ TDM irrigated 1994

Figure 4.3. Bean dry matter production as influenced by triple superphosphate (TSP). Vertical bars represent standard errors of means (S.E.).



- TDM rainfed 1993
- TDM rainfed 1994
- ▲ TDM irrigated 1993
- ▼ TDM irrigated 1994

Figure 4.4. Bean dry matter production as influenced by Minjingu phosphate rock (MPR). Vertical bars represent standard errors of means (S.E.).

The variation in HI values ranged between 21% in the control plots with freshly applied P during the 1993 rainfed experiment to 49% in plots that received 88 kg P ha⁻¹ MPR with a crop grown under irrigation in the 1993 growing season. The HI values generally increased with the increase in seed yield, and irrigated experiments had higher HI values than rainfed experiments in both seasons. Similar results have also been reported by Sirait *et al.* (1994) in lima bean (*Phaseolus lunatus* L.). Interpreting the HI values in this study is difficult because of the defoliation, and petiole loss during maturation (after R₆) growth stage.

Expecting to include all plant tissues and obtain realistic values is impossible. Thus modified HI values such as those proposed by Shibata *et al.* (1980) would be appropriate. These would include the dry weight of abscised organs such as flowers, pods and leaves. From the obtained results, however, the assumption can be made that the increase in seed yield recorded in this study was due to the increase in HI. Also, at certain growth periods plants were not producing any more seed.

Seed yield plant⁻¹ in beans can be expressed as a product of three components: pods per plant, seed per pod, and seed weight (Fageria *et al.*, 1991). Among these yield components, pods per plant has often been recommended as an indirect selection criterion for increasing yield, because of its higher and more consistent correlation with yield (Bennet *et al.*, 1977; Sarafi, 1978).

In their study, Nienhuis and Singh (1986) concluded that high seed yield in bean is associated with high number of pods m⁻², seeds pod⁻¹, and all architectural traits except branches plant⁻¹. Data for yield components are presented in Tables 4.3a to 4.3d. Pods plant⁻¹ was the component found that consistently affected by the applied P. Similar results have been reported by Fageria (1989) and Yan *et al.* (1995 b). Some studies using indeterminate

bean cultivars (Acosta-Gallegos and Shibata, 1989) revealed that the number of pods plant⁻¹ was the yield component most adversely affected by water stress.

Table 4.3a. Yield components in beans grown with fresh applied P treatments under rainfed conditions.

Treatments	Pods plant ⁻¹	Seeds pod ⁻¹	Seed wt (g 100 seed ⁻¹)	Total seed wt (g plant ⁻¹)
-----1993 Growing Season -----				
0 kg P ha ⁻¹	5.10 (0.29) ¹	3.40 (0.06)	42.60 (2.08)	7.39 (0.69)
22 kgP ha ⁻¹ -TSP	6.20 (0.35)	4.00 (0.12)	41.17 (0.76)	10.21 (0.77)
22 kgP ha ⁻¹ -MPR	6.90 (0.38)	3.70 (0.12)	42.13 (2.55)	10.76 (0.64)
44 kgP ha ⁻¹ -TSP	7.10 (0.74)	3.90 (0.23)	40.03 (0.83)	11.08 (1.39)
88 kgP ha ⁻¹ -TSP	5.90 (0.21)	4.10 (0.09)	43.97 (1.48)	10.64 (0.29)
88 kgP ha ⁻¹ -TSP	5.30 (0.31)	3.80 (0.06)	41.43 (1.09)	8.34 (1.04)
176kgP ha ⁻¹ -MPR	6.30 (0.54)	3.50 (0.10)	43.87 (2.77)	9.67 (0.36)
-----1994 Growing Season -----				
0 kg P ha ⁻¹	4.50 (0.27)	2.60 (0.52)	28.54 (0.83)	3.34 (0.44)
22 kgP ha ⁻¹ -TSP	6.40 (0.27)	3.00 (0.44)	31.86 (3.57)	6.12 (0.62)
22 kgP ha ⁻¹ -MPR	6.40 (0.64)	2.70 (0.32)	29.52 (2.66)	5.10 (1.73)
44 kgP ha ⁻¹ -TSP	6.70 (0.65)	4.10 (0.41)	35.67 (2.41)	9.80 (1.86)
88 kgP ha ⁻¹ -TSP	5.80 (0.82)	4.00 (0.43)	35.47 (0.16)	8.23 (1.41)
88 kgP ha ⁻¹ -TSP	6.60 (1.80)	2.70 (0.06)	31.64 (0.54)	5.64 (1.51)
176kgP ha ⁻¹ -MPR	6.50 (0.95)	2.30 (0.63)	27.56 (1.86)	4.12 (1.39)

¹Figures in parentheses show the standard error values.

Table 4.3b. Yield components in a bean crop grown with fresh applied P treatments under irrigated conditions.

Treatment	Pods plant ⁻¹	Seeds pod ⁻¹	Seed wt (g 100 seed ⁻¹)	Total seed wt (g plant ⁻¹)
-----1993 Growing Season-----				
0 kg P ha ⁻¹	6.9 (0.52) ¹	3.6 (0.36)	41.83 (1.68)	10.39 (1.24)
22kgP ha ⁻¹ -TSP	7.4 (0.70)	4.7 (1.01)	44.70 (1.01)	15.55 (1.77)
22kgP ha ⁻¹ -MPR	6.9 (0.23)	3.5 (0.30)	44.57 (0.29)	10.76 (1.29)
44kgP ha ⁻¹ -TSP	7.4 (0.46)	4.1 (0.09)	42.67 (0.86)	12.94 (0.86)
88kgP ha ⁻¹ -TSP	7.4 (0.29)	4.0 (0.24)	42.07 (0.91)	12.45 (0.63)
88kgP ha ⁻¹ -MPR	7.4 (0.40)	3.5 (0.08)	41.77 (0.47)	10.82 (0.57)
176kgP ha ⁻¹ -MPR	7.5 (0.34)	4.1 (0.15)	42.73 (3.12)	13.14 (0.75)
-----1994 Growing Season-----				
0 kg P ha ⁻¹	4.6 (0.76)	3.3 (0.21)	37.30 (1.54)	5.66 (1.15)
22kgP ha ⁻¹ -TSP	6.8 (1.05)	3.0 (0.12)	36.01 (1.97)	7.35 (0.56)
22kgP ha ⁻¹ -MPR	6.4 (1.46)	3.5 (0.34)	34.49 (6.55)	7.73 (2.00)
44kgP ha ⁻¹ -TSP	5.0 (1.01)	3.6 (0.12)	39.12 (2.46)	7.04 (1.37)
88kgP ha ⁻¹ -TSP	6.5 (0.23)	3.6 (0.42)	42.53 (1.02)	9.95 (0.74)
88kgP ha ⁻¹ -MPR	4.8 (0.32)	3.3 (0.17)	38.75 (3.22)	6.14 (0.32)
176 kgP ha ⁻¹ -MPR	5.2 (0.42)	3.3 (0.35)	36.32 (4.16)	6.23 (1.32)

¹Figures in parentheses show the standard error values.

Table 4.3c. Yield components in a bean crop grown with fresh applied P treatments under irrigated conditions.

Treatment	Pods plant ⁻¹	Seeds pod ⁻¹	Seed wt (g 100 seed ⁻¹)	Total seed wt (g plant ⁻¹)
-----1993 Growing Season-----				
0 kg P ha ⁻¹	6.9 (0.52) ¹	3.6 (0.36)	41.83 (1.68)	10.39 (1.24)
22kgP ha ⁻¹ -TSP	7.4 (0.70)	4.7 (1.01)	44.70 (1.01)	15.55 (1.77)
22kgP ha ⁻¹ -MPR	6.9 (0.23)	3.5 (0.30)	44.57 (0.29)	10.76 (1.29)
44kgP ha ⁻¹ -TSP	7.4 (0.46)	4.1 (0.09)	42.67 (0.86)	12.94 (0.86)
88kgP ha ⁻¹ -TSP	7.4 (0.29)	4.0 (0.24)	42.07 (0.91)	12.45 (0.63)
88kgP ha ⁻¹ -MPR	7.4 (0.40)	3.5 (0.08)	41.77 (0.47)	10.82 (0.57)
176kgP ha ⁻¹ -MPR	7.5 (0.34)	4.1 (0.15)	42.73 (3.12)	13.14 (0.75)
-----1994 Growing Season-----				
0 kg P ha ⁻¹	4.6 (0.76)	3.3 (0.21)	37.30 (1.54)	5.66 (1.15)
22kgP ha ⁻¹ -TSP	6.8 (1.05)	3.0 (0.12)	36.01 (1.97)	7.35 (0.56)
22kgP ha ⁻¹ -MPR	6.4 (1.46)	3.5 (0.34)	34.49 (6.55)	7.73 (2.00)
44kgP ha ⁻¹ -TSP	5.0 (1.01)	3.6 (0.12)	39.12 (2.46)	7.04 (1.37)
88kgP ha ⁻¹ -TSP	6.5 (0.23)	3.6 (0.42)	42.53 (1.02)	9.95 (0.74)
88kgP ha ⁻¹ -MPR	4.8 (0.32)	3.3 (0.17)	38.75 (3.22)	6.14 (0.32)
176 kgP ha ⁻¹ -MPR	5.2 (0.42)	3.3 (0.35)	36.32 (4.16)	6.23 (1.32)

¹Figures in parentheses show the standard error values.

Table 4.3d. Yield components in beans grown with annual applied P treatments under irrigated conditions.

Treatment	Pods plant ⁻¹	Seed pod ⁻¹	Seed wt (g 100 seed ⁻¹)	Total seed wt (g plant ⁻¹)
-----1993 Growing Season-----				
0 kg ha ⁻¹	5.93 (0.92) ¹	3.50 (0.15)	45.77 (0.63)	9.49 (1.43)
22kgP ha ⁻¹ -TSP	7.50 (0.35)	3.60 (0.15)	44.97 (2.37)	12.14 (0.48)
22kgP ha ⁻¹ -MPR	7.47 (0.56)	4.37 (1.14)	46.80 (2.06)	15.27 (1.67)
44kgP ha ⁻¹ -TSP	6.97 (0.30)	3.67 (0.43)	44.47 (1.07)	11.38 (1.27)
88kgP ha ⁻¹ -1-TSP	8.47 (0.23)	3.47 (0.07)	42.43 (0.61)	12.47 (0.43)
88kgP ha ⁻¹ -MPR	8.37 (0.69)	3.70 (0.31)	37.53 (2.79)	11.62 (0.91)
176kgP ha ⁻¹ -MPR	6.87 (0.35)	3.23 (0.13)	42.10 (1.27)	9.34 (0.38)
-----1994 Growing Season-----				
0 kg P ha ⁻¹	3.93 (0.09)	4.30 (0.10)	35.69 (0.71)	6.03 (0.09)
22kgP ha ⁻¹ -TSP	4.70 (0.61)	4.13 (0.34)	35.60 (1.71)	6.91 (1.08)
22kgP ha ⁻¹ -MPR	5.17 (0.95)	4.25 (1.40)	31.69 (0.74)	6.96 (1.23)
44kgP ha ⁻¹ -TSP	5.47 (0.75)	4.07 (1.39)	35.71 (0.55)	7.95 (1.40)
88kgP ha ⁻¹ -TSP	6.25 (0.87)	3.53 (0.20)	34.97 (1.53)	7.69 (0.24)
88kgP ha ⁻¹ -MPR	4.93 (0.35)	4.77 (0.86)	35.16 (0.53)	8.27 (1.39)
176kgP ha ⁻¹ -MPR	5.93 (0.35)	3.83 (0.49)	34.99 (1.05)	7.95 (0.58)

¹Figures in parentheses show the standard error values.

Present results do not show significant effects on pods plant⁻¹ within experiments. However, the differences were observed between seasons. The 1994 season had a lower average number of pods plant⁻¹ than those in the 1993 season, regardless of whether the experiment was rainfed or irrigated. Seeds pod⁻¹, and seed size (g seed) were also significantly affected by P levels. Total seed weight per plant (g plant⁻¹) was lower in the control plots. The lowest value was from the rainfed conditions under fresh applied P during 1994 season.

Plants in control plots aborted a larger number of pods at R₆ growth stage (i.e., pods less than 10 mm in length) than plants in plots with applied P. This may have resulted from competition among developing pods for photosynthate, and metabolites, which in turn were affected by available P to the plants. The control plots had higher abortion of individual ovules, thus resulting in lower seeds per pod. In the 1994 growing season for example, the control plots under rainfed conditions gave 3.34 g plant⁻¹, while other plots with applied P ranged between 4.1 and 15.3 g plant⁻¹. However, plots that had the highest seed yield plant⁻¹ did not necessarily give the highest seed yield per hectare. These results were also affected by the TDM loss due to fallen leaves, petiole, and some stems (branches) at maturity harvest. Further, there was a reduction in plant population at harvest time (Appendices 5a and 5b) due to attack of pests such as termites and some rodents.

Relative Agronomic Effectiveness of MPR

The relative agronomic effectiveness (RAE) values from this study are shown in Table 4.4. On the basis of the regression coefficients of the P response curves, the values calculated for RAE of MPR (TSP=100%) in increasing bean TDM production differed with seasons and experiments. All RAE values of MPR were below 50% except that of the 1993 fresh applied P and rainfed experiment (RAE=64.59), and that of the 1994 annual applied P irrigated experiment (RAE=64.15). The RAE values reported in this study are lower than values reported with highly reactive sources such as Gafsa PR (Tunisia), but are similar to values reported for medium reactive Huila PR (Colombia) using bean as the test crop (Chien and Hammond, 1978), and Central Florida PR (USA) using soybean crop (Chien *et al.* (1990).

The results based on DMRT ($P=0.05$) showed that TSP was generally as effective as MPR under rainfed, and irrigated conditions. However, based on orthogonal comparisons, the results showed that TSP was as effective ($P=0.05$) as MPR in 13 (three from irrigated conditions) out of 24 comparisons (Table 4.5). Among the six comparisons where TSP showed more significant effect than MPR, four were from the irrigated experiment. MPR was significantly more effective in five comparisons, from the irrigated experiments.

The low agronomic effectiveness reported in this study may have been due to bean TDM production being higher with control treatments than those usually reported under ordinary experimental conditions (in Tanzania). As indicated earlier, the soil texture at both experimental sites exhibit high P retention capacity. Using the scale suggested by Chien *et al.* (1990), MPR showed the characteristics of low to medium agronomic effectiveness. This observation is also supported by the NAC reactivity characteristics shown in Table 4.1.

Table 4.4. Values of coefficients (b) and relative agronomic effectiveness (RAE) of Minjingu phosphate rock and triple superphosphate in terms of bean total dry matter production.

Fresh applied P				Annual applied P				
Rainfed experiment								
1993		1994		1993		1994		
b _i	RAE	b _i	RAE	b _i	RAE	b _i	RAE	
MPR	9.12	64.59	3.56	34.46	3.15	20.65	5.59	34.40
TSP	14.12	100.00	10.33	100.00	15.25	100.00	16.25	100.00
Irrigated experiment								
MPR	3.15	20.66	5.59	34.44	2.97	18.15	1.79	64.15
TSP	15.25	100.00	16.25	100.00	16.36	100.00	2.79	100.00

$$Y_i = Y_0 + b_i \ln X, X > 1$$

where

Y_i = Yield obtained with source (i)

Y_0 = Yield obtained with no P application

b_i = Regression coefficient source

Table 4.5. Summary of orthogonal comparisons between triple superphosphate and Minjingu phosphate rock in agronomic effectiveness.

Fresh applied P			
Season		Results	
		Rainfed	Irrigated
1993	Treatment compared		
	22 kg P TSP vs 22 kg P MPR	A=B*	A<B*
	88 kg P TSP vs 88 kg P MPR	A=B*	A<B*
	44 kg P TSP vs 176 kg P MPR	A=B	A=B
1994	22 kg P TSP vs 22 kg P MPR	A=B*	A<B*
	88 kg P TSP vs 88 kg P MPR	A=B*	A>B*
	44 kg P TSP vs 176 kg P MPR	A>B	A=B
Annual applied P			
1993	22 kg P TSP vs 22 kg P MPR	A=B*	A<B*
	88 kg P TSP vs 88 kg P MPR	A=B*	A>B
	44 kg P TSP vs 176 kg P MPR	A<B	A>B
1994	22 kg P TSP vs 22 kg P MPR	A=B*	A>B*
	88 kg P TSP vs 88 kg P MPR	A=B*	A<B
	44 kg P TSP vs 176 kg P MPR	A=B	A=B*

* A=B based on DMRT (P=0.05)

A=Triple superphosphate (TSP)

B=Minjingu phosphate rock (MPR)

SUMMARY AND CONCLUSIONS

Soil pH, extractable P, and exchangeable Ca increased in plots where P fertilizers were applied regardless of type or rate of fertilizer used. However, increases were higher in plots that received high rates of MPR. Crop growth stages and maturity periods depended mainly on the night cool temperatures during the growth period and not on P treatments. The irrigated experiments accumulated greater amounts of TDM. The decline of TDM production (kg ha^{-1}) at harvest maturity was attributed mainly to the decrease in plant population.

Despite irrigation and other optimum agronomic conditions provided to the experiments, seed yields in this study were still low when compared with yields from medium altitude, i.e., 900 to 2100 m. This was mainly due to disease (ascochyta blight) attack to the seed. Also, beans do not do well in locations below the altitude of 600 m. High temperatures ranging between 20° and 30° C, such as those observed during the rainfed experimental periods, result in poor fruit set.

This study shows that MPR can result in raising the soil pH (liming effect) when applied at high rates such as 88 and 176 kgP ha^{-1} . However, such high rates would not be economically feasible for Tanzanian resource-poor farmers. This may be due to high transportation costs per unit of P delivered to the farm because of MPR's low nutrient content compared to TSP. The RAE of MPR with respect to TSP, in terms of increasing total dry matter, were lower than TSP (RAE=100%). Overall analyses show that, despite some suggestions that MPR can be as effective as superphosphate fertilizers in bean production, TSP is a superior fertilizer in areas with soil pH values allowing bean production.

Since MPR is known to be a complex mixture of apatites (Van Kauwenbergh, 1991), before the ore is packed for commercial distribution, characterization studies should be performed from each sample of ore. This will identify the best material that is effective as a P source for direct application when used under appropriate conditions.

Finally, more laboratory, greenhouse, and field research should be conducted to delineate all factors influencing the effectiveness of MPR for direct application. Furthermore, apart from low soil pH, low soil P, and low soil Ca, MPR use should be advocated in areas where irrigation can be applied in bean production.

RECOMMENDATIONS FOR FUTURE RESEARCH

The information obtained in this study needs to be complemented. Therefore, using the experience gained in this study, the following is suggested for future research.

1. Research on partially acidulated MPR should be initiated in Tanzania to determine whether this technology can provide a means whereby MPR could be an agronomically better fertilizer for bean and other crops' production.
2. Since there is a problem of manual direct application of fine (dusty) MPR as observed during this study, research on compacted dust free materials of MPR for farmers should be initiated.
3. Different bean cultivars should be used for further evaluation of MPR as different bean varieties have different characters of P efficiency which are heritable (Yan *et al.*, 1995 a and 1995 b). Also, different locations including those with high bean yield potential e.g., >1000 m.a.s.l.) should be included in future studies.

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CHAPTER 5

**RESIDUAL EFFECTS OF PHOSPHOROUS APPLICATION ON
BEAN PRODUCTION UNDER RAINFED AND IRRIGATED CONDITIONS**

ABSTRACT

There is no documented information on residual effectiveness due to P fertilizer application on beans in Tanzania. Therefore, a two year experiment was set up at Sokoine University of Agriculture in Morogoro, Tanzania to evaluate the effects of direct, and residual values of triple superphosphate (TSP) and Minjingu phosphate rock (MPR) on bean growth and yield under rainfed and irrigated conditions. For the direct effects plots received annual fertilizers in the 1993 and the 1994 growing seasons. Different plots received fresh P during both growing seasons. For residual effects, P applications were made once in the 1993 growing season. Comparison of bean performance was done using parameters from freshly applied P, annual P and residual P in 1994. Each block had three replications, and each replication received seven P treatments. All fertilizer treatments were broadcast and incorporated in each plot at planting. Basal N application was made at 80 kg ha⁻¹ in form of the urea. The N was split applied at planting and at flowering. Growth parameters were taken at a two week interval. Phosphorous concentration in plant tissues was analyzed at the

same interval. At maturity, total dry matter, seed yield, and yield components were analyzed. Results showed that P uptake increased with increasing application of P rates. The TSP fertilizer effect on leaf P concentration at R_1 growth stage was similar to that of MPR fertilizer. Using Duncan multiple range test (DMRT at $P=0.05$) TSP had similar effects on total dry matter (TDM) production under fresh and residual P. However, under orthogonal comparisons ($P=0.05$) results showed that TSP performed better than MPR at 44 and 88 kg P ha⁻¹ under rainfed conditions. Under irrigated conditions, TSP and MPR had no significant agronomic effectiveness. The relative agronomic effectiveness (RAE) values of MPR with respect to TSP (RAE=100%) in terms of influencing TDM production were 12% under rainfed conditions, and 41% under irrigated conditions. Results showed that the effect of soluble P (TSP) fertilizer were higher in terms of influencing TDM production than that of MPR fertilizer one year after their application under rainfed conditions when equal amounts were compared.

LITERATURE REVIEW

Residual effects of plant nutrients are defined as influence on crops following the crop to which the nutrients are applied (Black, 1993). When P fertilizer is applied in most soils, P is retained close to the site of application. Unlike nitrate, which has little affinity for soil particles, fertilizer P is rapidly adsorbed or precipitated in acid mineral soils. Much of the P that is applied to the soil is rapidly, and irreversibly fixed by adsorption hysteresis (Pierzynski *et al.*, 1994). Adsorbed P is normally considered to be slowly available, and capable of gradually replenishing the soil solution in response to plant uptake by desorption. Mechanisms

for P loss are physical erosion of the top soil, and loss of solution P in surface runoff, while leaching is minimal (Schuman *et al.*, 1973). Therefore, P is a long-lasting nutrient because of its strong interaction with soil (Black, 1993).

There are generally three zones of reactions between the soil and a P fertilizer granule (Barrow, 1980). For example, when monocalcium phosphate ($\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$) is applied to the soil the fertilizer particle is surrounded by soluble P available to the plants. The insoluble phosphates are then formed with Ca^{2+} , or Fe^{3+} , and Al^{3+} cations depending on the soil pH (Lindsay and Moreno, 1960). At this stage, the P is still readily available to plant roots since most of it is located at the surface where exudates from the plant can encourage exchange. In time, the P penetrates the crystal and a small portion is found near the surface. Under such conditions P becomes fixed (Brady, 1990). The second zone of reaction which has complexes of Ca^{2+} , or Fe^{3+} or Al^{3+} and P, contains the residue of P fertilizer (Barrow, 1980).

Organic matter may decrease or increase the ability of soils to adsorb P. This ability depends on the organic matter and the association with cations such as Fe, Al, and Ca, which are capable of adsorbing P while associated with organic matter (Moshi *et al.*, 1974; Sample *et al.*, 1980; Kalkafi *et al.*, 1988). Under practical conditions, the residual effectiveness of the applied fertilizer is influenced by fertilizer type, nutrient type, time, management, environmental factors, the crop that removes some of the nutrient supplied and finally, the inter-relationships of these factors (Devine *et al.*, 1968; Bolland *et al.*, 1988).

Experimental results by Juo and Ellis (1968) showed that when soluble P is applied to acid soils, P precipitated rapidly to form colloidal Al-P and Fe-P. Because of their smaller particle sizes, greater surface area and amorphous structure, these colloidal forms were

readily available to plants. However, these colloidal phosphates crystallized to form hydrated compounds such as variscite ($\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$), and strengite ($\text{FePO}_4 \cdot 2\text{H}_2\text{O}$) which were much less available for plant uptake. From their study results, they concluded that, during the first stage of P fixation, the rate of crystallization was the factor that controlled the relative availability of P from the variscite and strengite in acid soils. With time, strengite crystallized at a much faster rate than variscite under favorable environmental conditions. Thus, in the second stage of P fixation, the relative portion of the colloidal form to the crystalline form was the factor that controlled the relative availability of the variscite and strengite in the acid soils. In the third and final stage, when both forms had completed the process of crystallization, specific surface and crystal structure became important in controlling P availability. Devine *et al.* (1968) obtained results that showed that the effectiveness of granular dicalcium phosphate was greater one year after application than when freshly applied. Some studies have shown that phosphate rock fertilizers persist in the soil up to 40 years longer than soluble P fertilizers. However, most experimental work show that residual effects of soluble P fertilizers are usually greater than those from PRs in the first three - four years after application when equal amounts of P are applied (Khasawneh and Doll, 1978; Le Mare, 1991; Choudhary *et al.*, 1994).

Reports on residual effectiveness due to P fertilizers in Tanzania are scarce, and where such studies have been conducted P uptake has not been measured. Among the few studies reported is that by Marandu *et al.* (1975) on NPK fertilizer applied on pasture and maize on ferrisol soils at Morogoro. In other studies using double superphosphate (DSP), and MPR fertilizers, positive residual effects have been reported by Scaife (1968) with cotton on granitic, sandy soil at Ukiriguru. Higher residual effects by MPR than water soluble P

fertilizers in the second or third season after application in a maize crop was reported by Mowo and Gama (1988). At Katumani in Kenya, MPR also showed a substantial residual value on a maize crop compared to TSP and single superphosphate (SSP) two to five years after application (Bromfield *et al.*, 1981; IFDC, unpublished report, 1990⁶).

A major problem encountered by bean producing farmers in Tanzania is the high amounts of P fertilizer application needed to meet the crop's requirements. The most common practice of correcting this P deficiency is by applying a heavy initial P fertilizer ($>50\text{kg P}_2\text{O}_5 \text{ ha}^{-1}$) to the crop every growing season. Such a recommendation is expensive to the resource poor-farmers of Tanzania. Therefore, the hypothesis in this study is that because (i) the P fertilizer types and rates recommended for application, and (ii) the soil type on which the bean crop is grown in Tanzania, the P fertilizers applied can result in substantial residual effects for the crop. Thus, this study was initiated with the aim of assessing the residual effectiveness of MPR relative to TSP on bean (*Phaseolus vulgaris* L.) crop growth, and yield during the successive season. Results on residual effects of fertilizer P from a single cropping season following its application are reported.

MATERIALS AND METHODS

Details on materials and methods are as given in Chapter 2 (for blocks A and B). When this study was initiated in the 1993 growing season, an extra block C was also set up so that it could be used as a control block in the 1994 growing season (i.e., to provide a

⁶Minjingu phosphate rock marketing study: A marketing plan for Minjingu Phosphapte Co. (MIPCO) in Arusha, Tanzania. International Fertilizer Development Center, P.O. 2040, Muscle Shoals, AL 35660.

comparison with the fresh P application). Therefore, block C received fertilizer P only in the successive growing season of 1994. Blocks A and B received the P treatments at sowing in 1993.

Bean response assessment for residual P was made by taking crop growth and yield measurements one year following the P application. This was done by taking measurements from the second-year crop response on the plots in block A, in relationship to the plots in the control block (C) that received fresh P fertilizer in the 1994 growing season. Plots in block B also served as controls in the first (1993) growing season. However, an additional application of P fertilizer was made in the second growing season of the experiment to block B.

Initial soil pH, extractable P, and exchangeable Ca levels were analyzed in blocks A and B at the beginning of the 1993 growing season (Tables 2.1), and at the beginning of the 1994 growing season (Table 4.2 a); and for block C as indicated in Table 5.1. The soil analysis of samples taken immediately before planting the first crop in 1993 for blocks A and B (Table 2.1) and in 1994 for block C (Table 5.1), are considered to be more representative of the soil chemical environment during the experiments reported in this study. In the 1994 growing season, P fertilizer treatments were broadcast, and incorporated at planting at both sites in blocks B and C. Post-harvest soil chemical characteristics for blocks A and C were taken seven days after harvest (Table 5.2).

Table 5.1. Pre-plant soil characteristics at 0-12 cm layer for Block C at the experimental sites during the 1994 season.

Soil characteristic	Experimental site	
	Rainfed	Irrigated
Moisture (%) ^a	17.14	21.10
pH:H ₂ O	4.80	5.30
Bray I (ppm)	1.20	2.20
Ca (meq 100g ⁻¹ soil)	2.39	3.99

^aVolumetric moisture content.

Growth parameters such as total dry matter (TDM kg ha⁻¹), leaf area index (LAI), plant height (cm), and crop growth rate (CGR) were determined as described in Chapter 2 and Chapter 4. Plant samples were collected, prepared, and analyzed for nutrients as described in Chapter 3. TDM, seed yield (kg ha⁻¹), and yield components; and relative agronomic effectiveness (RAE) were determined as given in Chapter 4. Statistical analyses were conducted using MSTAT-C Statistical Package (Michigan State University, 1993). Lastly, crop performance from block A (residual P), block B (annual P), and block C (fresh P) were compared at the end of the 1994 growing season. Orthogonal comparisons were used to compare the agronomic influence of TSP versus that of MPR.

RESULTS AND DISCUSSION

Effects of Residual P Treatments on Soil pH, Extractable P, and Exchangeable Ca.

The effects of TSP and MPR application were similar to those discussed in Chapter 4. With the exception of the control plots, soil pH, available P, and exchangeable Ca increased in plots that received P fertilizers (Table 5.2). Such results may have been due to the interaction between the P fertilizer used, and the soil characteristics as indicated by Anderson *et al.* (1985), Chien *et al.* (1987), Robinson *et al.* (1992), and Sale and Mokuwunye (1993).

Phosphorous Concentration

The uptake of P was higher in freshly applied P blocks than in residual P conditions; and higher in irrigated experiment than in the rainfed experiment (Tables 3.2 and 5.3). According to Piggot (1986), high levels of P fertilizer resulted in what can be regarded as adequate P concentration at flowering. Fresh P had higher P concentration than residual P under rainfed conditions. Patterns of P concentration, distribution, and accumulation were similar to those discussed in Chapter 3. High concentration values of P observed in this study may have been due to the small leaf size (area) as indicated by values of LAI (Table 5.3). Such a condition may sometimes result in accumulation of P concentration values of the limiting nutrient (Hiatt and Massey, 1958, Adu-Gyamfi *et al.*, 1990). Although these results

show that plants had high leaf P concentration, there is no indication that the high P application in either fresh, annual or residual applied P satisfied the crop requirement for P.

Table 5.2. Soil pH, Bray-I P and calcium levels in post-harvest soil at 0-12 cm layer in Blocks A and C at the end of 1994 growing season.

Treatment	Soil pH		Bray I (ppm)		Ca (meq)	
Rainfed experiment						
	<i>A</i>	<i>B</i>	<i>A</i>	<i>B</i>	<i>A</i>	<i>B</i>
0 kg P ha ⁻¹	4.75	4.81	1.43	1.65	1.91	2.01
22 kk P ha ⁻¹ TSP	4.81	4.92	3.12	2.35	2.29	2.78
22 kg P ha ⁻¹ MPR	4.78	5.01	3.01	3.37	3.82	3.63
44 kg P ha ⁻¹ TSP	4.69	5.12	3.90	3.01	2.57	3.77
88 kg P ha ⁻¹ TSP	4.82	5.01	3.23	3.69	2.92	3.59
88 kg P ha ⁻¹ MPR	4.65	4.89	5.40	4.94	3.31	3.89
176 kg P ha ⁻¹ MPR	4.64	4.98	7.32	6.91	2.96	3.94
Irrigated experiment						
0 kg P ha ⁻¹	5.49	5.40	1.80	1.64	2.16	3.31
22 kk P ha ⁻¹ TSP	5.50	5.43	2.07	2.35	2.07	3.81
22 kg P ha ⁻¹ MPR	5.74	5.47	2.42	2.37	3.54	3.89
44 kg P ha ⁻¹ TSP	5.65	5.65	2.01	3.01	3.99	3.93
88 kg P ha ⁻¹ TSP	5.87	5.60	3.17	3.69	3.24	3.81
88 kg P ha ⁻¹ MPR	5.96	5.53	4.10	4.94	4.05	4.08
176 kg P ha ⁻¹ MPR	5.53	5.53	6.31	6.91	5.05	4.89

A: represents data from block A

B: represents data from block C

Table 5.3 Influence of residual P on TDM and seed production; P concentration and maximum leaf area index.

Treatment	Residual P Bray I (ppm)	TDM kg ha ⁻¹	Seed kg ha ⁻¹	Leaf P at R ₁ (%)	Max. LAI
Rainfed experiment					
Triple superphosphate					
0 kg P ha ⁻¹	1.21	1060 (544)*	289 e	0.29	1.05
22 kg P ha ⁻¹	3.89	1950 (234)	571 de	0.35	1.45
44 kg P ha ⁻¹	5.45	2499 (458)	852 abc	0.29	1.49
88 kg P ha ⁻¹	9.35	3314 (99)	815 a	0.36	1.54
Minjingu phosphate rock					
0 kg P ha ⁻¹	1.21	1060 (544)	289 e	0.29	1.05
22 kg P ha ⁻¹	6.89	2124 (165)	693 bcd	0.32	1.85
88 kg P ha ⁻¹	10.65	2608 (318)	833 ab	0.42	1.50
176kg P ha ⁻¹	11.94	2006 (297)	688 cd	0.33	1.24
Irrigated experiment					
Triple superphosphate					
0 kg P ha ⁻¹	2.53	1232 (109)	347 b	0.25	1.03
22 kg P ha ⁻¹	4.03	1670 (251)	672 a	0.30	1.05
44 kg P ha ⁻¹	5.61	1921 (415)	761 a	0.40	1.49
88 kg P ha ⁻¹	7.31	1879 (127)	857 a	0.41	1.13
Minjingu phosphate rock					
0 kg P ha ⁻¹	2.53	1232 (109)	347 b	0.25	1.03
22 kg P ha ⁻¹	5.91	1907 (361)	703 a	0.38	1.54
88 kg P ha ⁻¹	8.66	2124 (523)	757 a	0.39	1.33
176kg P ha ⁻¹	12.45	1910 (137)	703 a	0.41	1.55

*Values in parentheses represent standard errors of the means. Means within the column for seed yield not followed by the same letter are significantly different at 0.05 level using Duncan's Multiple Range Test.

Crop Growth, Leaf Area Index, and Total Dry Matter Production.

The seasonal pattern of growth and development were similar to those discussed in Chapter 4. Under rainfed conditions, the CGR value ranged from $3.15 \text{ g m}^{-2} \text{ day}^{-1}$ in the control plots to $10.4 \text{ g m}^{-2} \text{ day}^{-1}$ in the plots that received 22 kg P ha^{-1} (MPR). Under irrigated conditions, the CGR values ranged from $3.25 \text{ g m}^{-2} \text{ day}^{-1}$ in the control plots to $12.4 \text{ g m}^{-2} \text{ day}^{-1}$ in plots that received 44 kg P ha^{-1} (TSP). The lowest CGR values in the control plots had the lowest LAI, TDM and seed yield. However, the highest CGR values did not result in highest LAI, TDM or seed yield (data not shown). Residual P effects on TDM, seed yield, and LAI production are shown in Tables 5.3. The irrigated experiment resulted in higher TDM production than the rainfed experiment. Other variables such as plant population (plants m^{-2}), leaf number on main stem and plant height (cm), all followed similar trends as discussed in Chapter 2 and Chapter 4.

The LAI values from the residual P blocks were lower than those measured from the annual, and freshly applied P plots. Maximum LAI values ranged from 1.05 in control plots to 1.85 in plots that received 22 kg P ha^{-1} in the form of MPR under rainfed conditions. Under irrigated conditions, maximum LAI values ranged from 1.03 in control plots to 1.55 in plots that received 176 kg P ha^{-1} in the form of MPR. Such low values of leaf area may have influenced the high values of P concentrations observed in this study as suggested by Hiatt and Massey (1958). Further, since leaf area is critical for crop light interception (Shibles and Weber, 1965), the low LAI observed here may have substantially influenced crop growth and total dry matter yield.

Seed Yield Components.

Effects of residual P on seed yield plant⁻¹, and yield components are shown in Table 5.4. Fertilizer TSP had the highest yield plant⁻¹ under rainfed conditions, ranging from 6.7 to 11.1 g plant⁻¹. On the other hand, MPR resulted in the seed yield plant⁻¹ ranging from 8.2 to 10.3 g plant⁻¹. Since seed yield in bean is expressed as a product of pods plant⁻¹, seeds pod⁻¹ and seed weight (Fageria *et al.*, 1991), current results show that the low yield per plant observed under irrigation may have been due to the low number of seeds pod⁻¹.

Seed yield (kg ha⁻¹) was statistically non-significant within treatments, except in the control plots which had lowest values (Table 5.3). Such results may have been influenced by the diseases that attacked the seeds while the crop was still in the field. Ascochyata blight, a fungal disease caused by *Phoma* spp, was an important disease especially in the irrigated experiment that matured under cool temperature, high humidity and had abundant water from irrigation. All these made the environment conducive for the disease.

Table 5.5 illustrates the RAE of fresh and residual P from MPR as compared to TSP. The influence of fresh P in terms of TDM production were similar in both experiments. However, under residual P the rainfed experiment had a lower RAE (12%), and the irrigated experiment had a higher RAE (41%). Such results confirm earlier observations reported in Chapter 4 that MPR effectiveness in TDM production was higher under irrigation conditions. These results, however, represent a relatively short period of time for an evaluation of residual effectiveness since the second crop was grown in a successive season limiting the period to only one year.

Table 5.4. Yield components for a bean crop grown with residual P in the 1994 season.

Treatments	Pods plant ⁻¹		Seeds pod ⁻¹		Seed wt (g 100 seed ⁻¹)	Total seed wt (g plant ⁻¹)
-----Rainfed experiment-----						
0 kg P ha ⁻¹	5.5	(0.7) ¹	4.0	(1.0)	28.4 (1.5)	6.2 (2.8)
22kgP ha ⁻¹ -TSP	5.4	(0.9)	3.8	(0.3)	32.2 (2.3)	6.7 (1.2)
22kgP ha ⁻¹ -MPR	7.2	(0.9)	4.0	(0.4)	28.3 (0.2)	8.2 (2.3)
44kgP ha ⁻¹ -TSP	7.8	(0.7)	4.3	(0.6)	33.2 (2.9)	11.1 (1.3)
88kgP ha ⁻¹ -TSP	7.7	(0.6)	4.1	(0.6)	35.6 (1.5)	11.1 (1.9)
88kgP ha ⁻¹ -MPR	6.3	(5.5)	5.0	(0.6)	32.6 (0.7)	10.3 (1.9)
176kgP ha ⁻¹ -MPR	7.0	(0.2)	4.5	(0.3)	31.1 (2.1)	9.8 (0.4)
-----Irrigated experiment-----						
0 kg P ha ⁻¹	4.9	(0.7)	3.6	(0.3)	35.3 (1.5)	6.2 (1.6)
22kgP ha ⁻¹ -TSP	6.8	(0.1)	4.0	(0.3)	33.1 (2.7)	8.9 (0.6)
22kgP ha ⁻¹ -MPR	4.9	(0.9)	3.9	(0.3)	37.4 (0.6)	7.2 (0.6)
44kgP ha ⁻¹ -TSP	7.1	(1.4)	3.9	(0.4)	36.9 (2.1)	10.3 (1.9)
88kgP ha ⁻¹ -TSP	8.1	(0.8)	4.0	(0.4)	33.9 (2.5)	10.9 (1.5)
88kgP ha ⁻¹ -MPR	6.5	(1.1)	3.7	(0.4)	37.2 (2.7)	8.9 (1.7)
176kgP ha ⁻¹ -MPR	7.0	(0.8)	3.3	(0.3)	38.6 (2.1)	8.9 (1.9)

¹Figures in parentheses show the standard error values.

Table 5.5. Values of coefficients (β) and relative agronomic effectiveness (RAE) of Minjingu phosphate rock and triple superphosphate in terms of bean total dry matter production from fresh and residual P in the 1994 season.

Rainfed experiment				
Fresh applied P			Residual P	
	β_i	RAE		
	β_i	RAE	β_i	RAE
MPR	3.6	34.5	3.	12.
TSP	10.3	100.	24.8	100.
Irrigated experiment				
MPR	5.6	34.4	2.8	41.
TSP	16.3	100.	6.7	100.

$$Y_i = Y_0 + \beta_i \ln X, X > 1$$

where

Y_i = Yield obtained with source (i)

Y_0 = Yield obtained with no P application

β_i = Regression coefficient source

X = Rate of P applied

Under rainfed conditions orthogonal comparisons showed that TSP had a higher agronomic effect than MPR on TDM production at 44 and 88 kg P ha⁻¹, but lower effect at 22 kg P ha⁻¹ (Table 5.6). However, under irrigated conditions, TSP had similar effects as MPR on TDM production. The higher residual effects on yield from soluble P fertilizer (TSP) than MPR in the first year after application shown in this study agree with the results reported by Khasawneh and Doll (1978); Le Mare (1991); and Choudhary *et al.* (1994). Fresh applied

P, in the form of TSP, resulted in a significant effect in three of the nine comparisons (two of these under irrigated conditions), while MPR performed better than TSP at only 22 kg P ha⁻¹ under irrigated conditions.

Table 5.6. Summary of orthogonal comparisons between triple superphosphate and Minjingu phosphate rock in agronomic effectiveness from freshly applied and residual P for the 1994 season.

Freshly applied P		
Treatment comparisons	Experiment	
	Rainfed	Irrigated
22 kg P TSP vs 22 kg P MPR	A=B*	A<B*
88 kg P TSP vs 88 kg P MPR	A=B*	A>B
44 kg P TSP vs 176 kg P MPR	A>B	A>B
Residual applied P		
22 kg P TSP vs 22 kg P MPR	A<B*	A=B*
88 kg P TSP vs 88 kg P MPR	A>B*	A=B*
44 kg P TSP vs 176 kg P MPR	A>B*	A=B*

* A=B based on DMRT (P=0.05)

A represents triple superphosphate (TSP)

B represents Minjingu phosphate rock (MPR)

Comparison of responses of a bean crop to residual, fresh, and annual P application are shown in Figure 5.1 for TSP fertilizer and in Figure 5.2 for MPR fertilizer. The response curves of residual applied P were initially steep for rainfed experiments in both seasons, but were almost flat and no response under the irrigated conditions of the 1993 growing season. With the exception of the 1994 growing season under the irrigated conditions, the response curves of annual applied P were steep. Response of bean crop to TSP under all three fertilizer regimes was consistent with the fertilizer amount applied. The exception was with the results of the 1994 growing season where the rainfed experiments resulted in higher TDM production than did the irrigated plots. As indicated earlier, such results may have been due to the attack by rodents which resulted in lower plant population at harvest maturity. In general, the responses of bean to MPR were inconsistent. For example, the response curve under rainfed conditions in 1993, and that under irrigation in 1994 show that a yield plateau was not reached. It was also interesting to observe that there was a progressive decline in TDM production with higher rates of MPR for rainfed and irrigated conditions under residual P (Figure 5.2).

The results from this were unexpected. As the extracted soil P increased, the crop yield (TDM) decreased. Such phenomenon of decreasing crop yield with increasing available P needs more investigation. It should be pointed out, however, that yields recorded in residual plots at irrigated site could have been influenced by flooding effects that took place in the previous season. The floods might have contaminated the plots by moving the P treatments from one plot to another (soil carryover). These results show that there was no clear pattern of response of MPR under residual and annually applied fertilizer P.

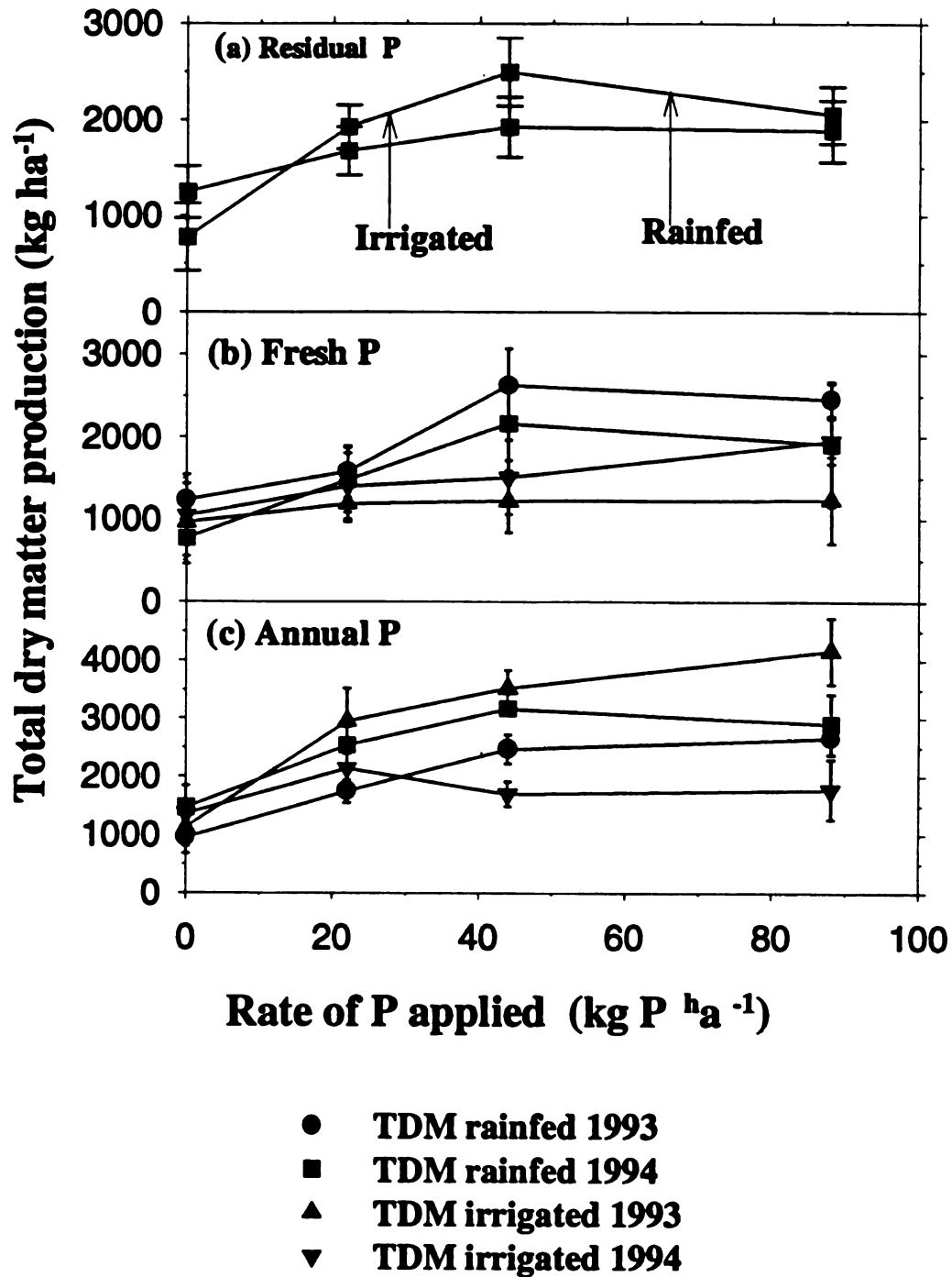


Figure 5.1. Comparison of responses of bean crop to residual, fresh, and annual application of different levels of TSP under rainfed and irrigated conditions.

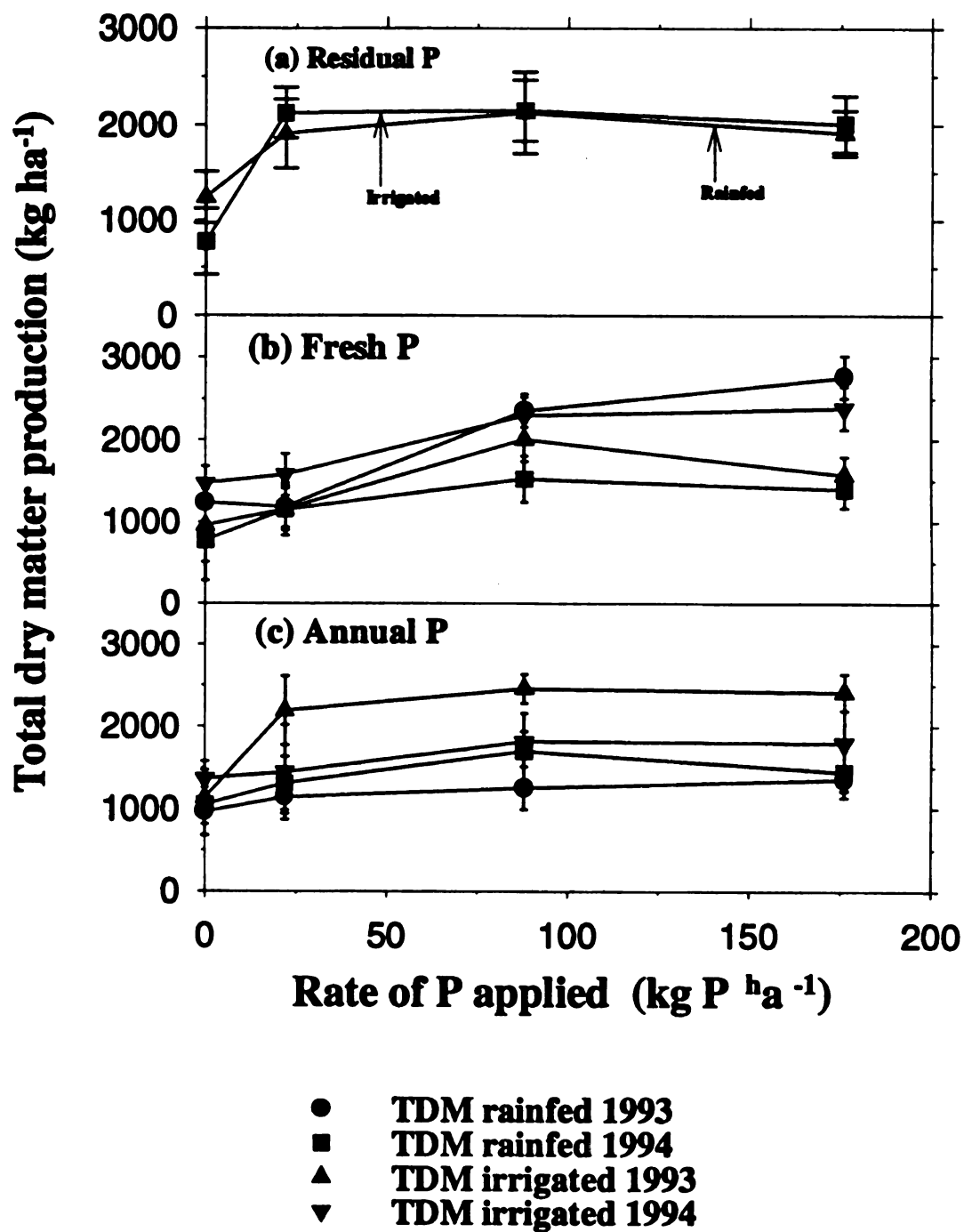


Figure 5.2. Comparison of responses of bean crop to residual, fresh, and annual application of different levels of MPR under rainfed and irrigated conditions.

SUMMARY AND CONCLUSIONS

Generally, annual applied P was more effective than fresh and residual P in TDM production. Significant differences between the residual effects of MPR and TSP sources were evident using orthogonal comparisons. At 44 and 88 kg P ha⁻¹ residual agronomic effectiveness of MPR was lower than that of TSP 12 months after application under rainfed and irrigated conditions. With fresh applied P, TSP had significant effects in most comparisons while MPR performed better than TSP only at 22 kg P ha⁻¹ under irrigated conditions. From orthogonal contrasts and RAE values, it is concluded that MPR could be used to a better advantage for bean crop grown under irrigated conditions than rainfed conditions.

The unexpected, inconsistent behavior of response to residual MPR one year after application in the two experiments provides a sound basis for further research on residual P relationship with between response of bean crop to MPR, soil properties and crop management. Bean seed yields reported from residual P were higher than those usually recorded by most farmers who usually practice annual fertilizer P application. Farmers' low yields usually average 600 kg/ha (Silbernagel and Teri, 1990) and could be due to late planting, use of low yielding varieties, poor soil fertility, water stress, vermin, pest, disease, and roaming livestock attack which are common field hazards.

RECOMMENDATIONS FOR FUTURE RESEARCH

The present short-term results show inconsistencies when rainfed and irrigated experiments are compared. This suggests that residual P effectiveness on bean yield should be continued so as to obtain information on the long-term fate of TSP and MPR when applied to the acid soils in Tanzania. This should include the identification of form (s) of P availability to plants relative to seasons after fertilizer(s) application. Knowledge from effects of long-term P fertilization may help in understanding how such a practice may influence the sustainability of Tanzania's agriculture.

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APPENDICIES

Appendix 1a. Soil profile description at the rainfed experimental site.

Order: Oxisol soils with pedogenic horizons that are mixtures principally of kaolinite hydrated oxides and quartz, and are low in weatherable minerals.

Suborder: Orthox

0 - 20 cm: Reddish brown (2.5 YR3/2), moist, dark reddish brown (2.5 YR3/4); sand loam, weak medium granular structure, slightly hard when dry, fine and medium roots; traces of mica and quartz fragments.

20 - 80 cm: Dark red (2.5 YR 3/6), moist; dark red (2.5 YR 3/6), dry; sandy clay; weak medium structureless, soft when dry; very few fine roots; small amount of quartz fragments; diffuse boundary.

80 - 100 cm: Red (2.5 YR 4/6), moist, clay loam; structureless, very friable when moist; traces of roots, some Fe-Mn concentrations.

The watertable was below 100 cm at the time of sampling. The profile was well drained with permeability classification 0.40 according to Ritchie *et al.* (1990).

The dominant clay was earlier determined as of Kaolinite type by Kesseba *et al.* (1972).

Appendix 1b. Soil profile description at the irrigated experimental site.

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- Order:** Alfisol: Gray to brown surface horizon.
- Suborder:** Udalf: Seasonally saturated with water; when drained beans, maize grow well. Moderately slopping.
- 0 - 20 cm:** Dusty red (2.5 YR 3/2) moist, dark grayish brown (10 YR 3/2); sand clay loam, weak medium granular structure; nonstick when dry; plastic when wet; coarse roots, fine roots, Fe concentrations, small amounts of yellowish (10 YR 5/6) and reddish (2.5 YR 4/6) material scattered throughout the horizon, clear smooth boundary.
- 20 - 40 cm:** Dark greyish brown (10 YR 3/2); sand clay loam, structureless; slightly stick and slightly plastic when wet; abundant fine roots; Fe-concentrations; few fine faint diffuse mottlings; gradual smooth boundary.
- 40 - 80 cm:** Dark greyish brown (10 YR 4/2), sandy loam, structureless; abundant Fe-concentrations, meddium distinct mottling, some pebbles visible; gradual smooth boundary.
- 80 - 100 cm:** Dark greyish brown (10 YR 4/2) moist, loam, structureless; abundant Fe-concentrations, medium distinct mottling.

The ground water-table was below 100 cm depth at the time of sampling. However, during the rainy season it came up to 50 cm.

Drainage is moderately slow with permiability class (SWON) of 0.05 according to Ritchie *et al.* (1990).

Both Kaolinite and Montmorillonite (Smectite) types in varying quantities as determined by Kesseba *et al.* (1972).

Appendix 2a. Daily weather data for the 1993 growing season at Sokoine University of Agriculture, Morogoro.

Day of Year	Month	Day	Temperature °C		Solar Radiation (MJ m ⁻²)	Rainfall (mm)	
			Maxim.	Minim.		Experiment Rainfed	Irrigated
93091	April	01	31.8	20.4	20.3	0.6	0.0
93092	April	02	31.6	20.2	21.3	0.0	0.0
93093	April	03	30.0	20.9	12.5	5.0	0.0
93094	April	04	29.5	19.1	12.9	0.0	0.3
93095	April	05	30.5	20.7	17.1	0.3	28.9
93096	April	06	31.0	19.6	19.1	28.9	21.9
93097	April	07	31.4	21.0	18.1	21.9	8.3
93098	April	08	29.0	20.2	14.4	8.3	0.0
93099	April	09	30.0	21.0	12.9	0.0	0.1
93100	April	10	30.5	21.0	15.5	0.1	26.4
93101	April	11	30.4	19.6	19.0	26.4	0.0
93102	April	12	31.0	21.4	16.7	2.7	0.0
93103	April	13	31.0	20.9	18.7	8.5	8.5
93104	April	14	28.7	21.6	10.6	8.3	8.3
93105	April	15	28.8	21.0	10.6	36.1	36.1
93106	April	16	29.0	20.4	17.6	2.6	2.1
93107	April	17	28.5	20.6	14.3	4.6	4.6
93108	April	18	30.2	20.0	21.2	12.5	12.5
93109	April	19	30.0	20.5	15.3	33.2	33.2
93110	April	20	29.5	20.1	14.7	26.1	26.1
93111	April	21	27.0	20.5	8.8	19.2	19.2
93112	April	22	29.2	20.8	16.0	17.1	17.1
93113	April	23	27.7	21.0	10.8	13.6	13.6
93114	April	24	29.0	21.1	12.6	15.6	5.0
93115	April	25	28.5	21.7	10.6	18.8	18.8
93116	April	26	29.3	21.3	12.6	10.6	10.6
93117	April	27	31.0	21.5	19.9	0.0	0.0
93118	April	28	30.5	20.6	14.2	3.3	3.3
93119	April	29	30.7	20.3	17.2	13.4	0.0
93120	April	30	31.0	21.4	16.7	0.0	0.0
Mean values			29.9	20.7	15.2	13.5	9.9

Appendix 2a. (cont'd).

93121 May	01	31.5	20.8	17.1	3.9	3.9
93122 May	02	32.0	21.1	15.7	7.0	7.0
93123 May	03	30.2	21.1	14.3	5.0	5.0
93124 May	04	28.0	20.6	11.6	8.9	8.9
93125 May	05	30.0	21.0	12.3	2.5	0.6
93126 May	06	31.8	21.6	16.1	0.0	0.0
93127 May	07	31.1	19.9	21.1	0.0	0.0
93128 May	08	29.2	19.9	17.7	0.0	0.0
93129 May	09	29.0	21.2	11.9	24.4	24.4
93130 May	10	31.1	20.0	16.2	0.0	0.0
93131 May	11	30.3	21.0	14.3	26.5	26.5
93132 May	12	28.6	21.2	14.3	0.0	0.0
93133 May	13	26.4	18.4	11.8	0.0	0.0
93134 May	14	27.0	19.5	9.8	0.0	0.0
93135 May	15	26.2	20.2	9.8	0.5	0.5
93136 May	16	27.0	19.0	8.8	0.1	0.1
93137 May	17	29.0	17.0	11.4	0.0	0.0
93138 May	18	28.0	16.0	18.8	0.0	0.0
93139 May	19	27.5	15.6	9.7	2.1	2.1
93140 May	20	28.5	19.4	15.3	2.7	2.7
93141 May	21	25.7	19.7	19.5	1.4	1.4
93142 May	22	29.5	20.1	9.0	7.5	7.5
93143 May	23	28.0	19.2	16.2	1.8	1.8
93144 May	24	28.4	20.5	15.5	3.0	0.0
93145 May	25	30.4	19.9	17.9	3.5	2.0
93146 May	26	28.5	19.5	17.4	3.0	0.0
93147 May	27	30.1	19.0	13.4	3.0	0.0
93148 May	28	28.9	19.9	17.6	2.0	0.0
93149 May	29	30.0	17.5	16.9	0.0	0.0
93150 May	30	29.0	17.1	20.4	2.9	2.4
93151 May	31	29.0	19.5	16.2	4.4	4.4
Mean values		28.8	19.6	14.7	5.5	2.0

Appendix 2a. (cont'd).

93152 June	01	30.0	18.5	17.0	5.4	0.0
93153 June	02	29.2	16.8	18.2	13.7	0.0
93154 June	03	28.0	16.2	13.2	0.0	0.0
93155 June	04	28.5	17.0	13.4	0.0	0.0
93156 June	05	29.2	17.0	16.0	0.0	0.0
93157 June	06	25.5	16.3	11.1	0.0	0.0
93158 June	07	27.3	14.7	11.8	0.0	0.0
93159 June	08	28.4	14.5	19.5	0.0	0.0
93160 June	09	28.4	14.5	18.6	0.0	0.0
93161 June	10	27.4	14.6	14.8	1.0	1.0
93162 June	11	27.5	13.5	19.8	0.0	0.0
93163 June	12	24.8	13.5	10.1	0.0	0.0
93164 June	13	27.4	16.0	18.6	1.4	1.4
93165 June	14	27.0	14.0	8.8	0.0	0.0
93166 June	15	27.2	18.6	10.2	2.0	2.0
93167 June	16	26.1	16.1	14.2	0.0	0.0
93168 June	17	26.8	17.4	11.9	0.0	0.0
93169 June	18	26.0	16.0	12.9	0.0	0.0
93170 June	19	26.5	16.0	20.8	0.0	0.0
93171 June	20	27.0	17.1	15.8	0.0	0.0
93172 June	21	28.5	15.8	15.4	1.2	1.2
93173 June	22	28.0	16.1	15.8	0.0	0.0
93174 June	23	28.5	16.0	17.1	0.0	0.0
93175 June	24	28.0	17.5	21.7	0.0	0.0
93176 June	25	29.0	16.5	17.1	0.0	0.0
93177 June	26	27.6	13.5	13.3	0.0	0.0
93178 June	27	26.5	14.0	12.9	2.5	2.5
93179 June	28	26.4	18.0	12.9	5.6	5.6
93180 June	29	25.5	17.8	11.9	0.0	0.0
93181 June	30	26.6	17.3	14.9	0.0	0.0
Mean values		27.3	16.1	14.7	4.1	0.4

Appendix 2a. (cont'd).

93182 July 01	26.0	11.6	16.2	0.0	0.0
93183 July 02	27.0	15.1	14.1	0.0	0.0
93184 July 03	28.0	13.5	18.8	0.0	0.0
93185 July 04	27.4	13.8	19.5	0.0	0.0
93186 July 05	25.5	15.8	16.6	0.0	0.0
93187 July 06	27.5	16.7	16.6	0.0	0.0
93188 July 07	28.3	16.3	11.5	0.0	0.0
93189 July 08	26.0	17.2	16.2	0.0	0.0
93190 July 09	26.5	17.5	17.9	0.0	0.0
93191 July 10	28.0	16.2	13.5	0.0	0.0
93192 July 11	28.4	15.2	13.3	0.0	0.0
93193 July 12	24.5	16.3	16.2	0.0	0.0
93194 July 13	27.5	17.6	19.0	1.3	1.3
94195 July 14	25.0	14.9	8.0	0.0	0.0
93196 July 15	28.7	16.5	19.5	0.0	0.0
93197 July 16	27.0	17.4	10.4	0.7	0.7
93198 July 17	24.5	17.5	19.9	1.4	1.4
93199 July 18	26.6	18.1	11.7	1.8	1.8
93200 July 19	25.9	17.3	9.5	0.5	0.5
93201 July 20	25.5	16.9	12.7	0.0	0.0
93202 July 21	23.0	15.5	11.9	0.0	0.0
93203 July 22	25.0	16.7	13.4	0.0	0.0
93204 July 23	26.0	14.9	5.9	0.0	0.0
93205 July 24	26.0	10.0	9.8	0.0	0.0
93206 July 25	25.4	11.2	17.4	0.0	0.0
93207 July 26	26.0	13.1	17.1	0.0	0.0
93208 July 27	28.5	12.0	15.9	0.0	0.0
93209 July 28	28.0	14.6	13.9	0.0	0.0
93210 July 29	28.5	16.1	19.0	0.0	0.0
93211 July 30	28.8	16.7	13.9	0.0	0.0
93212 July 31	32.2	16.8	15.3	0.0	0.0
Mean values	27.3	20.5	15.1	0.1	0.1

Appendix 2a. (cont'd).

93213 August 01	27.1	17.3	14.6	0.0	0.0
93214 August 02	27.9	15.2	16.7	0.0	0.0
93215 August 03	26.7	15.0	14.4	0.0	0.0
93216 August 04	25.7	18.5	12.6	0.0	0.0
93217 August 05	21.0	16.9	5.2	0.0	0.8
93218 August 06	25.5	16.4	11.3	1.0	1.0
93219 August 07	25.4	15.3	12.7	0.0	0.0
93220 August 08	26.6	14.6	19.3	0.0	0.0
93221 August 09	26.4	15.2	11.6	0.0	0.0
93222 August 10	28.8	16.9	15.9	0.0	0.0
93223 August 11	27.4	17.1	22.6	0.0	0.0
93224 August 12	29.0	13.5	22.3	0.0	0.0
93225 August 13	28.2	14.7	18.1	0.0	0.0
93226 August 14	28.5	15.8	15.8	0.0	0.0
93227 August 15	25.4	16.3	16.2	0.0	0.0
93228 August 16	27.5	12.0	16.1	0.0	0.0
93229 August 17	27.2	16.7	14.3	0.0	0.0
93230 August 18	27.4	14.6	15.3	0.0	0.0
93231 August 19	28.3	15.0	17.8	0.0	0.0
93232 August 20	26.6	14.5	14.5	0.0	0.0
93233 August 21	27.2	14.7	16.0	0.0	0.0
93234 August 22	27.6	15.4	15.3	0.0	0.0
93235 August 23	28.6	15.8	14.2	0.0	0.0
93236 August 24	28.5	17.3	13.2	0.0	0.0
93237 August 25	27.5	17.1	10.8	0.0	0.0
93238 August 26	27.5	18.7	20.8	0.2	0.2
93239 August 27	29.4	16.4	18.6	0.0	0.0
93240 August 28	29.0	17.3	10.0	0.0	0.0
93241 August 29	25.4	17.0	12.0	1.2	1.2
93242 August 30	29.0	18.5	15.5	0.0	0.0
Mean values	27.3	20.5	15.1	0.1	0.1

Appendix 2b. Daily weather data for the 1994 growing season at Sokoine University of Agriculture, Morogoro.

Day of Year	Month	Day	Temperature °C		Solar Radiation (MJ m ⁻²)	Rainfall (mm)	
			Maxim.	Minim.		Experiment Rainfed	Irrigated
94091	April	01	30.5	21.4	19.5	0.0	0.0
94092	April	02	32.0	17.1	16.3	0.0	0.0
94093	April	03	32.0	18.8	22.0	0.0	0.0
94094	April	04	30.0	19.9	12.5	0.0	0.3
94095	April	05	28.0	20.5	11.8	1.3	1.3
94096	April	06	28.0	20.3	10.6	31.9	31.9
94097	April	07	26.4	20.3	9.7	11.1	11.1
94098	April	08	29.5	18.1	13.2	6.9	6.9
94199	April	09	29.0	20.0	14.7	24.4	2.7
94100	April	10	27.5	20.5	10.9	24.2	8.3
94101	April	11	27.1	20.0	10.6	4.1	4.1
94102	April	12	29.4	19.8	15.0	15.0	0.0
94103	April	13	29.8	18.0	17.9	1.0	1.0
94104	April	14	30.1	19.2	15.7	0.0	0.0
94105	April	15	30.5	20.8	20.6	7.1	7.1
94106	April	16	30.5	20.4	12.7	2.6	0.0
94107	April	17	30.5	19.5	20.1	0.0	0.0
94108	April	18	33.3	20.0	17.8	0.0	0.0
94119	April	19	31.5	18.3	17.5	5.9	5.9
94110	April	20	28.5	20.2	12.5	7.2	4.6
94111	April	21	26.5	20.2	7.8	16.0	0.3
94112	April	22	31.0	20.6	19.1	14.0	14.0
94113	April	23	30.0	19.4	15.6	1.2	1.2
94114	April	24	27.0	20.3	9.0	26.0	18.0
94115	April	25	29.0	19.6	18.1	26.5	5.4
94116	April	26	29.0	18.8	11.7	35.0	0.8
94117	April	27	27.6	19.5	14.4	5.9	0.0
94118	April	28	28.4	17.0	14.5	0.0	0.0
94119	April	29	26.5	17.5	11.0	13.4	11.1
94120	April	30	23.5	19.6	13.7	33.0	33.2
Mean values			29.0	19.5	14.2	10.6	5.6

Appendix 2b. (cont'd).

94121 May	01	25.2	19.2	9.2	0.5	0.5
94122 May	02	24.5	19.8	6.8	8.0	5.4
94123 May	03	27.5	17.5	13.7	17.2	17.2
94124 May	04	28.5	19.5	14.4	16.1	16.1
94125 May	05	30.3	20.5	13.3	0.6	0.6
94126 May	06	30.7	19.8	18.1	0.6	0.6
94127 May	07	29.5	19.4	19.7	0.8	0.8
94128 May	08	27.0	19.5	10.6	0.0	0.0
94129 May	09	26.5	19.6	11.6	0.0	0.0
94130 May	10	27.3	18.8	11.1	0.0	0.0
94131 May	11	25.5	20.0	7.5	15.0	7.4
94132 May	12	25.5	19.0	6.7	8.4	8.4
94133 May	13	29.2	19.8	11.8	9.6	9.6
94134 May	14	27.5	19.4	11.0	0.0	5.7
94135 May	15	28.4	19.8	14.8	18.5	4.9
94136 May	16	29.5	19.5	14.1	0.0	0.0
94137 May	17	28.9	18.9	14.5	0.8	0.8
94138 May	18	29.2	19.0	16.0	1.1	1.1
94139 May	19	25.6	18.8	9.8	3.7	3.7
94140 May	20	28.6	19.0	16.2	6.9	3.6
94141 May	21	29.5	19.1	16.2	1.9	0.0
94142 May	22	27.8	18.7	14.3	0.5	0.0
94143 May	23	29.5	17.6	19.5	0.0	0.2
94144 May	24	28.6	17.1	18.8	0.0	0.0
94145 May	25	29.0	17.5	16.5	0.5	0.0
94146 May	26	26.0	19.0	11.2	0.0	0.0
94147 May	27	26.5	16.0	11.4	0.0	0.0
94148 May	28	26.0	15.1	11.1	0.0	0.0
94149 May	29	26.0	16.2	11.0	0.0	0.0
94150 May	30	25.0	16.0	6.4	1.9	1.4
94151 May	31	26.8	17.5	11.1	0.0	0.0
Mean values		27.6	18.6	12.9	5.9	2.9

Appendix 2b. (cont'd).

94152 June	01	26.8	13.2	18.6	0.0	0.0
94153 June	02	28.0	12.6	17.0	0.0	0.0
94154 June	03	28.5	14.5	19.0	0.0	0.0
94155 June	04	28.6	13.9	19.4	0.0	0.0
94156 June	05	29.0	15.7	17.1	0.0	0.0
94157 June	06	29.5	14.8	21.2	0.0	0.0
94158 June	07	29.3	14.1	20.7	0.0	0.0
94159 June	08	28.5	15.4	15.5	0.0	0.0
94460 June	09	27.5	15.0	14.3	0.0	0.0
94161 June	10	27.2	14.0	15.9	0.0	0.0
94162 June	11	27.5	12.4	19.5	0.0	0.0
94163 June	12	26.5	11.2	18.9	1.2	1.2
94164 June	13	28.3	11.0	17.1	0.0	0.0
94165 June	14	27.7	13.9	16.2	0.0	0.0
94166 June	15	26.2	16.3	11.5	0.0	0.0
94167 June	16	27.0	14.4	15.2	0.0	0.0
94168 June	17	28.5	13.0	18.7	0.0	0.0
94169 June	18	27.0	13.2	15.4	0.0	0.0
94170 June	19	25.0	13.8	12.6	0.0	0.0
94171 June	20	26.6	14.1	15.0	0.0	0.0
94172 June	21	25.5	13.7	13.2	0.2	0.2
94173 June	22	23.0	16.1	5.8	6.6	6.6
94174 June	23	28.5	16.2	17.1	0.0	0.0
94175 June	24	28.8	16.3	17.5	0.0	0.0
94176 June	25	28.5	14.2	16.9	0.0	0.0
94177 June	26	28.6	13.2	14.0	0.2	0.2
94178 June	27	29.0	17.0	17.5	0.0	0.0
94179 June	28	27.8	17.0	14.3	0.0	0.0
94180 June	29	27.0	16.6	12.9	0.0	0.0
94181 June	30	28.5	12.5	27.2	0.0	0.0
Mean values		27.6	14.3	16.4	0.3	0.3

Appendix 2b. (cont'd).

94182 July 01	29.0	13.9	17.8	4.7	4.7
94183 July 02	24.4	18.2	6.1	0.0	0.0
94184 July 03	27.4	17.1	12.9	0.2	0.2
94185 July 04	27.5	16.1	13.8	13.6	13.6
94186 July 05	28.0	18.0	16.5	1.1	1.1
94187 July 06	27.0	16.5	12.9	17.2	17.2
94188 July 07	25.5	17.4	10.6	0.0	0.0
94189 July 08	27.4	14.5	17.1	0.0	0.0
94190 July 09	28.0	14.5	17.4	0.0	0.0
94191 July 10	29.3	13.5	18.7	0.0	0.0
94192 July 11	29.2	15.1	16.9	0.0	0.0
94493 July 12	28.1	15.0	19.0	0.0	0.0
94194 July 13	25.0	16.1	10.8	0.0	0.0
94195 July 14	27.0	11.4	19.1	0.0	0.0
94196 July 15	26.5	10.2	19.0	0.0	0.0
94197 July 16	28.4	11.1	21.0	0.0	0.0
94198 July 17	27.0	10.8	16.2	0.0	0.0
94199 July 18	27.5	14.0	16.2	0.0	0.0
94200 July 19	27.6	13.7	18.3	0.0	0.0
94201 July 20	28.0	16.1	12.7	0.0	0.0
94202 July 21	27.0	17.5	15.9	0.0	0.0
94203 July 22	27.9	16.0	13.4	0.0	0.0
94204 July 23	29.0	17.4	10.3	0.0	0.0
94205 July 24	24.9	19.2	16.1	0.0	0.0
94206 July 25	28.7	14.8	16.1	0.0	0.0
94207 July 26	30.0	15.5	18.6	0.0	0.0
94208 July 27	30.0	16.2	19.3	0.0	0.0
94209 July 28	27.6	15.0	18.7	0.0	0.0
94210 July 29	27.0	16.0	18.2	0.0	0.0
94211 July 30	27.7	14.6	16.2	0.0	0.0
94212 July 31	26.2	16.8	7.0	0.0	0.0
Mean values	27.5	15.2	16.6	1.2	1.2

Appendix 2b. (cont'd).

94213 August 01	27.5	16.0	18.4	0.0	0.0
94214 August 02	26.5	15.1	11.0	8.4	8.4
94215 August 03	24.6	16.1	8.6	0.5	0.5
94216 August 04	25.9	16.6	12.5	0.0	0.0
94217 August 05	28.0	13.1	19.3	0.0	0.0
94218 August 06	28.0	14.6	22.9	0.0	0.0
94219 August 07	27.0	15.4	14.2	0.0	0.0
94220 August 08	27.5	15.5	18.1	0.0	0.0
94221 August 09	29.0	17.0	17.9	0.0	0.0
94222 August 10	30.3	14.1	18.1	0.0	0.0
94223 August 11	28.2	15.0	17.7	0.0	0.0
94224 August 12	28.5	17.4	14.0	0.0	0.0
94225 August 13	30.0	16.0	19.3	0.0	0.0
94226 August 14	29.0	14.7	19.9	0.0	0.0
94227 August 15	28.3	15.5	13.4	0.0	0.0
94228 August 16	28.2	16.8	16.8	0.0	0.0
94229 August 17	30.0	16.0	17.1	0.0	0.0
94230 August 18	29.0	14.8	17.8	0.0	0.0
94231 August 19	30.5	17.6	16.9	0.5	0.5
94232 August 20	24.5	17.2	6.3	0.5	0.5
94233 August 21	27.5	15.6	16.2	0.0	0.0
94234 August 22	28.6	14.1	19.9	0.0	0.0
94435 August 23	28.8	15.2	19.5	4.7	4.7
94236 August 24	27.5	16.8	15.7	0.0	0.0
94237 August 25	28.6	15.1	16.2	2.7	2.7
94238 August 26	28.5	17.4	12.4	1.0	1.0
94239 August 27	28.2	16.6	16.0	0.4	0.4
94240 August 28	28.6	15.8	16.2	0.0	0.0
94241 August 29	29.0	16.1	18.1	0.0	0.0
94242 August 30	29.5	15.2	18.5	0.0	0.0
Mean values	28.1	15.8	16.0	0.6	0.6

Appendix 3. Developmental stages of determinate bean (*Phaseolus vulgaris* L.) used in the study¹.

Days After Panting (DAP) Code	Growth Stage	Growth Stage Descriptions
7-14	V ₂	Crop emergence and establishment. Leaf edges no longer touch.
14 - 18	V ₃	Two to three nodes on the main stem including the primary leaf node. Two to three true leaves (trifoliolate leaves).
26 - 30	V ₄	Vegetative growth terminates in a flower cluster. 50% of plants with four nodes on main stem.
28 - 32	R ₁	50% of plants per plot with at least one open flower on any node (Flowering stage).
30 - 34	R ₂	50% of plants per plot with at least one flower at node immediately below the upper most node with a completely unrolled leaf.
35 - 40	R ₄	50% of plants per plot with a pod 2.0 cm long at one of the four upper most nodes with a completely unrolled leaf. Seeds not discernible by feel. (Early pod development).
42 - 46	R ₅	50% of plants per plot with seeds beginning to develop at one of the four uppermost nodes with a completely unrolled leaf. Seeds discernible by feel.

Appendix 3. (cont'd).

50 - 55	R ₆	50% of plants per plot containing full size seeds at one of the four uppermost nodes with completely unrolled leaf. Pods about 10cm long at first flower position. (Seed filling).
56 - 60	R ₇	Oldest pods with largest seeds. Pods developing over the whole plant. Most pods at full length. Point of maximum production reached.
63 - 67	R ₈	50% of plants per plot with leaves yellowing over half of the plant. Some pods drying. Physiological maturity.
65 - 77	R ₉	More than 80% pods yellowing. Less than 15% of leaves still green in color. Harvest maturity.

¹ Growth Stages Identified Visually According to:
 Fehr *et al.* (1971), and Nuland and Schwartz (1989).

Appendix 4a. Irrigation schedules for the 1993 season.

DOY	DAP	Amount of Water Applied (mm)	Crop Growth Stage ¹
145	-	-	Land preparation (V ₀) .
146	-	31.5	-
147	-	27.8	Planting date (VP).
152	4	33.8	-
154	6	50.0	-
157	9	-	50% Crop emergence (V ₁).
161	13	30.0	95% Crop emergence (V ₂).
162	14	27.5	First trifoliolate leaf (V ₃)
168	20	21.1	-
174	26	21.1	-
180	32	28.2	-
181	33	31.5	First flower in 50% of the plants (R ₁).
182	34	20.6	-
187	39	21.1	50% of the plants with pods of 2.0 cm long (R ₄).
191	43	21.1	-
195	47	24.5	-
198	51	24.5	-
204	56	20.8	-
208	60	21.7	>50% of the plants with mature pods (R ₆).
214	67	20.0	90% of plants with mature pods (R ₈). End of irrigation process.
218	77	-	90% of pods browning, 90% of leaves yellowing maturity, and harvest time (R ₉).

Total amount of water applied (mm) 476.8

DOY = Day of the year.

DAP = Days after planting.

¹According to Fehr *et al.* (1971), and Nuland and Schwartz (1989).

Appendix 4b. Irrigation schedules for the 1994 season.

DOY	DAP	Amount of water Applied (mm)	Crop growth stage ¹
120	-	-	Land preparation (V ₀).
128	-	-	Planting date (VP).
136	8	40.5	50% Crop emergence (V ₁).
140	12	-	95% Crop emergence (V ₂).
142	14	33.7	First trifoliate leaf (V ₃).
150	22	31.8	-
157	29	36.3	First flower in 50% of the plants (R ₁).
159	31	28.4	-
168	42	40.3	50 % of plant are with pods of 2.0 cm long (R ₄).
173	45	32.4	-
177	49	26.9	-
183	55	10.3	-
187	59	19.3	>50% of plants with full size beans (R ₆).
193	65	13.9	-
200	72	-	>90% plants with mature pods. End of irrigation process (R ₇).
207	76	-	>90% of the pods browning, 90% of leaves yellowing maturity, and harvest time (R ₉).

Total amount of water applied (mm) 313.80

DOY = Day of the year.

DAP = Days after planting.

¹According to Ferh *et al.* (1971), and Nuland and Schwartz (1989).

Appendix 5a. Plant population (plants m⁻²) at V₃ and R₉ from fresh applied P fertilizer regimes.

Treatments	1993 Season		1994 Season	
	V ₃	R ₉	V ₃	R ₉
Rainfed Experiment				
0 kg P ha ⁻¹	22.67 a*	17.33 a	18.67 a	13.67 a
22 kgP ha ⁻¹ TSP	22.67 a	18.00 a	22.69 a	15.33 a
22 kgP ha ⁻¹ MPR	22.33 a	17.33 a	21.43 a	16.33 a
44 kgP ha ⁻¹ TSP	21.33 a	17.67 a	19.54 a	14.67 a
88 kgP ha ⁻¹ TSP	21.67 a	17.33 a	21.67 a	16.67 a
88 kgP ha ⁻¹ MPR	21.33 a	18.00 a	22.00 a	16.00 a
176 kgP ha ⁻¹ MPR	21.00 a	19.00 a	21.33 a	14.33 a
MEAN	21.86	17.81	21.03	14.33
CV (%)	12.57	6.60	6.26	7.28
Irrigated Experiment				
0 kg P ha ⁻¹	20.00 a	19.00 a	21.00 a	18.00 ab
22 kgP ha ⁻¹ TSP	20.67 a	18.33 a	21.33 a	19.67 ab
22 kgP ha ⁻¹ MPR	20.33 a	17.67 a	21.67 a	20.67 a
44 kgP ha ⁻¹ TSP	19.67 a	18.00 a	18.00 a	16.67 ab
88 kgP ha ⁻¹ TSP	20.00 a	19.67 a	21.67 a	16.33 b
88 kgP ha ⁻¹ MPR	20.00 a	19.67 a	20.33 a	18.00 ab
176 kg P ha ⁻¹ MPR	20.00 a	19.00 a	22.00 a	19.00 ab
MEAN	20.10	18.76	20.89	18.33
CV (%)	11.58	13.89	13.61	11.71

*Means within the column for a given season and variable not followed by the same letter are significantly different at 0.05 level using Duncan's Multiple Range Test.

Appendix 5b. Plant population (plants m⁻²) at V₃ and R₃ from annual applied P fertilizer regimes.

Treatments	—1993 Season—		—1994 Season—	
	V ₃	R ₃	V ₃	R ₃
Rainfed Experiment				
0 kg P ha ⁻¹	24.00 a *	20.33 a	22.00 a	12.67 a
22 kgP ha ⁻¹ TSP	22.33 a	19.00 a	20.33 a	16.33 a
22 kgP ha ⁻¹ MPR	23.33 a	22.00 a	22.33 a	14.00 a
44 kgP ha ⁻¹ TSP	24.00 a	18.67 a	22.00 a	17.00 a
88 kgP ha ⁻¹ TSP	22.33 a	19.00 a	22.00 a	15.67 a
88 kgP ha ⁻¹ MPR	22.00 a	20.00 a	20.00 a	16.33 a
176 kg P ha ⁻¹ MPR	22.67 a	18.33 a	21.33 a	16.67 a
MEAN	22.81	19.57	21.42	15.52
CV (%)	6.70	11.30	10.43	18.86
Irrigated Experiment				
0 kg P ha ⁻¹	22.00 a	12.67 a	21.67 a	16.67 a
22 kgP ha ⁻¹ TSP	20.33 a	16.33 a	21.00 a	16.00 a
22 kgP ha ⁻¹ MPR	22.33 a	14.00 a	24.33 a	16.67 a
44 kgP ha ⁻¹ TSP	22.00 a	17.00 a	21.67 a	17.00 a
88 kgP ha ⁻¹ TSP	22.00 a	15.67 a	24.33 a	17.67 a
88 kgP ha ⁻¹ MPR	20.00 a	16.33 a	21.67 a	17.00 a
176 kg P ha ⁻¹ MPR	21.33 a	16.67 a	22.67 a	17.33 a
MEAN	21.42	15.52	22.48	16.91
CV(%)	8.64	9.22	8.20	12.45

* Means within the column for a given season and variable not followed by the same letter are significantly different at 0.05 level using Duncan's Multiple Range Test.

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