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Grain yield of wheat as affected by cropping sequence and fertilizer application in southeastern Ethiopia

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ABSTRACT

Cropping systems in the Ethiopian highlands consist primarily of cereals in rotation with grain legume and oilseed crops; the proportional allocation among crop species varies with altitude, rainfall, and soil type. Barley (*Hordeum vulgare* L.) tends to dominate in the highest altitudinal zones, while bread wheat (*Triticum aestivum* L.) is more common at medium altitudes on well-drained soils. A trial was established in 1992 at the Kulumsa and Asasa research sites in southeastern Ethiopia to evaluate interactions among wheat-based cropping sequences and annual applications of inorganic nitrogen (N) and phosphorus (P) fertiliser. Rotational crops included Ethiopian rapeseed (*Brassica carinata* L.), faba bean (*Vicia faba* L.), and barley. The results indicated significant rotational effects on wheat grain yield (GY), including enhanced GY in dicot vs. cereal rotations, in two year vs. three year rotations, in first year wheat after any break crop, and in rotation with faba bean vs. rapeseed. Interactions among cropping sequences and N and P fertiliser were also significant. Response to N was markedly reduced in two year rotations with any break crop, in first year wheat after any break crop, and after faba bean, in particular; this reflected higher soil N status in these cropping sequences. Conversely, P response was significantly enhanced in two year rotations and in the first wheat crop after any break crop, and in dicot-based rotations, particularly with faba bean. Presumably, this enhancement was the result of simultaneous improvement in soil N status and a reduction in wheat root pathogen and grass weed populations in these cropping sequences.

Key Words: Barley, crop rotation, faba bean, grain yield, nitrogen, phosphorus, rapeseed, *Triticum aestivum*, weed density

RESUME

Les systemes de culture sur les hauts plateaux ethiopiens reposent essentiellement sur la rotation cereales-legumineuses-oleagineux. Les proportions relatives des differentes cultures varient avec l'altitude, les precipitations et les conditions edaphiques. L'orge (*Hordeum vulgare* L.) domine a haute altitude, tandis que le ble tendre (*Triticum aestivum* L.) se rencontre plut“t aux altitudes intermediaires sur des sols bien draines. Un dispositif experimental a ete mis en place en 1992 dans les centres de recherche de Kulumsa et d'Asasa dans le sud-est ethiopien afin d'evaluer, l'interaction entre le schema de rotation et l'application annuelle d'engrais inorganique azote (N) et phosphore (P) au sein des systemes a base de ble. Le colza ethiopien (*Brassica carinata* L.), la feve (*Vicia faba* L.) et l'orge ont ete utilises comme cultures de rotation. Les resultats montrent un effet significatif de la rotation sur le rendement en grains du ble (RG): une rotation ble-dicotyledones se traduit par un RG plus eleve qu'une rotation ble-cereales; un cycle de rotation de deux ans conduit a un RG plus eleve qu'un cycle de trois ans; le RG augmente apres n'importe quelle culture de rotation; le RG de ble en rotation avec de la feve est superieur a celui de ble en rotation avec du colza. On observe egalement une interaction significative de la rotation culturale-fertilisation N et P. La reponse a la fertilisation N connait une importante diminution dans une rotation de deux ans quelle que soit la plante utilisee en rotation; on observe egalement une reduction en premiere annee apres n'importe quelle plante alternative, dans les rotations ble-dicotyledones et plus particulierement dans le cas de la feve. Ces resultats refletent la plus haute teneur du sol en azote dans les schemas de rotation consideres. Inversement, la reponse au phosphore augmente dans les rotations de deux ans, pendant la premiere annee apres n'importe quelle plante alternative, et dans les rotations a base de dicotyledones, en particulier la feve. On suppos que cette augmentation correspond aux effets combines de ces schemas de rotation : amelioration du bilan azote dans le sol, reduction des populations d'adventices et de pathogenes de la racine de ble.

Mots Cles: Azote, ble, colza, densite d'adventices, feve, orge, rendement en grains, rotation, phosphore, *Triticum aestivum*

INTRODUCTION

Sustainable agriculture has been defined as "the successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources" (TAC, 1988). The maintenance of long-term agricultural productivity depends on a number of biotic and abiotic factors all of which are dynamic in response to human intervention. Conservation tillage and crop rotation are considered to be the major means of maintaining agricultural productivity globally (Lal, 1989). Historically, very few agricultural research programmes in sub-Saharan African (SSA) have conducted multi-year or long-term agronomic trials to investigate the impact of crop production practices on the sustainability of the prevailing farming systems.

Practical rotation options for cropping systems in wheat (*Triticum* spp.) producing zones have been considered in only a few cases in SSA. Most of these studies have focused on the short-term benefits from break or precursor crops for wheat production (Hailu *et al.*, 1989). One eight year rotational study in Ethiopia provided extensive information on the impact of various cropping sequences on wheat grain yield (Amanuel and Tanner, 1991), but this particular set of trials contained several methodological flaws (Amanuel *et al.*, 1994).

Fertiliser rates have been recommended for wheat production in SSA without considering the sustainability of continuous fertiliser application. In Ethiopia, the high rates of nitrogen (N) applied to bread wheat plots in single season on-farm fertiliser trials had repercussions on soil pH levels, severity of wheat foliar disease, and weed incidence and competition (Tanner *et al.*, 1993). However, there are no reports available on the long-term effects of repeated N and phosphorus (P) application at the rates recommended for wheat production.

In the peasant farming systems of southeastern Ethiopia, cereals predominate, often occupying over 80% of the total cropped land each season (Chilot *et al.*, 1992). In the highland zones, bread wheat and barley (*Hordeum vulgare*) are the most common cereals in production, while faba bean (*Vicia faba*) and rapeseed (*Brassica carinata*) are the most common grain legume and oilseed crops, respectively.

The high proportion of wheat and barley in the highland cropping systems satisfies the short-term subsistence objectives of peasant farmers, but may prove disadvantageous in the long-term due to the absence of the inherent advantages of crop rotational systems. Several of the well-known benefits of crop rotation could be extremely valuable in the peasant farming sector: N fixation by legumes (Hargrove *et al.*, 1983); the interruption of weed (Heenan *et al.*, 1990), disease and insect cycles by dicotyledonous crops; crop diversification (Zentner and Campbell, 1988); improvement in soil tilth and a concomitant reduction in rainfall runoff and erosion (Higgs et al., 1990). In southeastern Ethiopia, a long-term decline in wheat yield was observed on Ministry of Agriculture seed production farms and on research centres. This decline, in the order of 22% over the period from 1969 to 1985, was attributed to the high proportion of cropland under wheat and barley, exceeding 50% in most seasons (Lindeman, 1986).

Several short-term studies in the Ethiopian highlands have examined the beneficial effects of break crops on wheat production. In one study, a faba bean break crop increased wheat grain yield by 1100 kg ha^-1, or 69% cf. the yield of second year continuous wheat (Hailu *et al.*, 1989); in a second study, faba bean increased wheat yield by 1000 kg ha^-1, or 44% cf. the yield of continuous wheat (Asefa *et al.*, 1992). However, no studies have previously considered the long-term effects of diverse cropping sequences on the Ethiopian cropping environment.

This paper presents results generated during the third and fourth years of one such ongoing study conducted at two locations in the major bread wheat production zone in southeastern Ethiopia. The objective of this trial is to evaluate the long-term effects of alternate crop rotation systems on wheat productivity and system sustainability, and on wheat response to inorganic fertiliser.

Materials and Methods

The rotation experiment was initiated during 1992 at the Kulumsa (8 degrees 02'N and 39 degrees 10'E) and Asasa (7 degrees 08'N and 39 degrees 13'E) research sites in Arsi Region of Ethiopia; the station soils are classified as an intergrade (between an eutric Nitosol and a luvic Phaeozem) and an eutric Nitosol, respectively. The soil clay content is approximately 45% at Kulumsa and 35% at Asasa. The average monthly mean minimum temperatures during the annual growing season are 10.6 and 6.7 C, and the corresponding average monthly mean maximum temperatures are 22.1 and 22.7 C, for Kulumsa and Asasa, respectively. Total annual precipitation is 824 and 665 mm, and that received during the June-November growing season is 504 and 472 mm, respectively (1970-95 means). The stations are situated at altitudes of 2200 and 2360 m a.s.l., respectively. The experimental sites used for the rotation trials had been sown to unfertilised wheat crops in 1991.

The trial incorporates three fundamental design principles consistently stressed in the statistical literature on multi-rotation experiments (Patterson, 1965; Preece, 1986; Cady, 1991):

Each phase of a specific rotation is present in the experiment every year to avoid assessing the effects of the rotational crops under differing seasonal conditions (i.e., confounding treatment and year effects). A three year cycle requires three plots in each replication to include all three phases of the rotation, while a two year cycle occurs in two phases each year.

Randomisation is essential to avoid anomalies from systematic assignment of treatments to field plots, and is fundamental to the validity of statistical analyses.

Replication is required to estimate experimental error and to minimise the magnitude of the standard error of treatment means.

The experiment was laid out in a split-plot design with crop rotations as main plots and fertiliser levels as subplots. The crop rotations are wheat-based, and reflect the predominant crops in the surrounding farming system: faba bean, rapeseed and barley. Treatments 1 to 15 (Table 1) comprise all phases of wheat in two and three year rotations with the three break crops, while treatment 20 consists of continuous wheat. Treatment pairs 16 and 17 and 18 and 19 comprise a partial sampling of all potential phases of complex six and four year rotations, respectively. The four fertiliser levels used during the first three years of the trial were the factorial combinations of 0 and 41 kg N ha^-1 with 0 and 20 kg P ha^-1. The four fertiliser treatments are maintained as fixed subplots over the duration of the trial. Starting in 1995, the low and high rates of N have been amended to 30 and 60 kg ha^-1 (from 0 and 41), while P rates remain constant. Urea and triple superphosphate are the sources of N and P, respectively. The trial was laid out in three replications, and the area of each main plot is 100 m2 with each fertiliser subplot having an area of 25 m2.

TABLE 1. Treatments included in the wheat-based crop rotation experiments at Kulumsa and Asasa

Treat.	Rot.-phase	1992	1993	1994	1995
1	1-1	Fb*	W	Fb	W
2	1-2	W	Fb	W	Fb
3	2-1	Ba	W	Ba	W
4	2-2	W	Ba	W	Ba
5	3-1	R	W	R	W
6	3-2	W	R	W	R
7	4-1	R	W	W	R
8	4-2	W	W	R	W
9	4-3	W	R	W	W
10	5-1	Fb	W	W	Fb
11	5-2	W	W	Fb	W
12	5-3	W	Fb	W	W
13	6-1	Ba	W	W	Ba
14	6-2	W	W	Ba	W
15	6-3	W	Ba	W	W
16	7-1	Fb	W	W	R
17	7-2	R	W	W	Fb
18	8-1	Fb	W	R	W
19	8-2	R	W	Fb	W
20	9	W	W	W	W

* Fb, W, Ba, R = faba bean, bread wheat, barley, and rapeseed, respectively

Tillage for this trial is based on the local ox-plough; crop protection practices simulate farmer practices (i.e., hand weeding); varietal selection is optimal for each crop, and open to change over the trial duration. The recommended varieties used for the various crop species were: for bread wheat, Enkoy in 1992-93, HAR 1709 in 1994, and HAR 1685 in 1995; for barley, Holker in 1992-93 and ARDU 12-60B in 1994-95; for faba bean, CS20DK in 1992-95; for rapeseed, Yellow Dodola in 1992-95. The seed rates used were 150 kg ha^-1 for bread wheat, 200 kg ha^-1 for faba bean, 15 kg ha^-1 for rapeseed, and 85 (in 1992 and 1993) and 130 (in 1994 and 1995) kg ha^-1 for barley. Pre-weighed amounts of seed and fertiliser were broadcast-applied on the soil surface of the appropriate plots after tillage by ox-plough, and were subsequently incorporated, in the traditional Ethiopian practice, by one pass of the ox-plough. Sowing dates were June 19 and July 1 in 1992, June 16 and July 6 in 1993, June 15 and July 6 in 1994, and June 15 and 28 in 1994 at the Asasa and Kulumsa sites, respectively.

Data were collected from each subplot on days to heading and maturity, plant height, weed density, and disease severity. At maturity, a net plot of 9 m2 was harvested by sickle at ground level for grain and biomass yield determination. Grain moisture contents were determined and yields adjusted to a 12.5% moisture basis for wheat and barley, 7% for rapeseed, and 10% for faba bean.

All data were subjected to ANOVA, analysing the four crop species separately. Subsequently, for the wheat data of 1994 and 1995, orthogonal contrasts were used to partition rotation main effects and rotation by fertiliser interaction effects into meaningful single degree of freedom components. Rotation (with 11 degrees of freedom) was partitioned into the following eight mutually orthogonal contrasts:

- wheat in dicot rotation vs. cereal rotation;
- wheat in 2 year vs. 3 year rotation;
- within 3 year rotations, first crop wheat vs. second crop wheat;
- wheat in rotation with faba bean vs. rapeseed;
- interaction of contrasts 1 and 2;
- interaction of contrasts 2 and 4;
- interaction of contrasts 1 and 3;
- interaction of contrasts 3 and 4.

Rotation by fertiliser interaction (with 33 degrees of freedom) was partitioned into eight mutually orthogonal contrasts:

1-2: (wheat in dicot rotation vs. cereal rotation) x (N or P effect);
3-4: (wheat in 2 year vs. 3 year rotation) x (N or P effect);
5-6: (within 3 year rotations, first crop wheat vs. second crop wheat) x (N or P effect);
7-8: (wheat in rotation with faba bean vs. rapeseed) x (N or P effect).

Results and Discussion

Seed or grain yields of the four crop species included in the rotation trial are summarised in Table 2 for the 1994 and 1995 seasons at the Kulumsa and Asasa sites. The summary of the effects on yield includes the main effect of N and P fertiliser for all crops, and rotation main and interaction effects for the principal crop, wheat. Yield responses to N and P fertiliser across the same crops, sites and seasons, expressed as N or P utilisation efficiency (UE) in kg grain or seed per kg nutrient added, are listed in Table 3.

TABLE 2. Seed or grain yields (kg ha^-1) of four crops. included ie the wheet-based crop rotation trial at Kulumsa and Asasa (1994-95) and significance levels of treatment effects

Crop		Kulumsa		Asasa	
		1994	1995	1994	1995
Faba bean	Mean yield	1856	1768	3485	1258
	C.V.(%)	20.7	11.6	11.6	17.5
	N effect	P<0.1	NS	NS	NS
	P effect	NS	NS	NS	*
Rapeseed	Mean yield	872	1063	1416	651
	C.V.(%)	27.8	33.5	15.5	21.7
	N effect	***	P<0.1	***	***
	P effect	***	NS	***	*
Barley	Mean yield	658	1638	971	861
	C.V.(%)	31.3	17.7	20.4	31.3
	N effect	*	*	***	NS
	P effect	NS	NS	**	**
Wheat	Mean yield	660	4153	1541	2400
	C.V.(%)	18.9	11.4	201	167
	Rotation effect	***	***	**	***
	N effect	***	***	***	***
	P effect	**	NS	NS	***
	Rot. x N interaction	***	**	NS	NS
	Rot. x P interaction	*	*	NS	*

*, **, ***: Significant at the 5, 1 and 0.1% level, respectively NS: Not significant

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TABLE 3. Yield response (kg grain or seed per kg nutrient) to N and P fertiliser^a of four crops included in the wheatbased crop rotation trial at Kulumsa and Asasa (1994-95)

		Kulumsa		Asasa	
Nutrient		1994	1995	1994	1995
Faba bean	N	.b	NS	NS	NS
	P	NS	NS	NS	9.6
Rapeseed	N	15.g	7.4	15.3	7.3
	P	16.5	NS	14.5	6.2
Wheat	N	1.9	20.7	5.9	8.3
	P	3.2	NS	NS	21.4
Barley	N	5.2	11.4	13.8	NS
	P	NS	NS	15.9	22.8

^a p contrast between 0 and 20 kg P ha^-1; N contrast between 0 and 41 kg N ha^-1 in 1994, and 30 and 60 kg N ha^-1 in 1995
^b N exerted a negative effect on faba bean seed yield
NS: Not significant (P>0.1)

Faba bean seed yield (SY) was particularly high during 1994 at Asasa (Table 2). Across the four trials, faba bean SY only responded positively to P in the Asasa 1995 trial, producing 9.6 kg seed per kg P applied (Table 3). Fertiliser N affected faba bean SY negatively in the Kulumsa 1994 trial, reducing yield from 1968 kg ha^-1 with 0 N to 1743 kg ha^-1 with 41 kg N ha^-1. Rotation marginally (P<0.1) affected faba bean SY in the Kulumsa 1995 trial: treatment 17 (R-W-W-Fb) at 1541 kg ha^-1 < treatment 2 (W-Fb-W-Fb) at 1948 kg ha^-1 and treatment 10 (Fb-W-W-Fb) at 1816 kg ha^- 1.

Rapeseed SY was markedly affected by N and P rates (Tables 2 and 3). N fertiliser increased rapeseed SY in each site-season: NUE ranged from 7.3 to 15.9 kg grain per kg N. In 3 of the 4 site-season combinations, P increased rapeseed SY: PUE ranged from 6.2 to 16.5 kg grain per kg P. Rotation affected rapeseed SY (P<0.01) in the Kulumsa 1994 trial: treatment 19 (Fb-W-R) at 1210 kg ha^-1 > treatment 5 (R-W-R) at 665 kg ha^-1 and treatment 8 (W-W-R) at 742 kg ha^-1. Thus, the precursor crop of faba bean grown 2 seasons previous had a beneficial effect on rapeseed. Amanuel et al. (1996b) reported elevated levels of soil nitrate in 1994 at Kulumsa in plots sown to faba bean in either 1992 or 1993, suggesting that this yield enhancement of rapeseed may have been due to increased soil N levels.

Barley grain yield (GY) was relatively low in all 4 trials (Table 2), reflecting the marginal adaptation of barley to altitudes below 2400 m a.s.l. in Ethiopia. Barley GY responded positively to N in 3 trials: NUE ranged from 5.2 to 13.8. Response to P was significant in 2 trials, and PUE ranged from 15.9 to 22.8 (Table 3). Rotation significantly (P<0.05) affected barley GY in the Kulumsa 1994 trial: treatment 3 (Ba-W-Ba) at 696 kg ha^-1 > treatment 14 (W-W-Ba) at 620 kg ha^-1. Perhaps, the low GY and hence nutrient uptake and removal by barley at this site was responsible for the positive response in 1994 to a preceding barley crop in 1992 vis-a-vis 2 years of wheat preceding barley.

Wheat GY increased markedly during 1995 as a result of the substitution of the relatively tall variety HAR 1709 by HAR 1685, a highly productive semi-dwarf variety (Table 2). The main effect of N on wheat GY was highly significant in all 4 trials: NUE ranged from 1.9 to 20.7 kg grain per kg N applied. The main effect of P was significant in 2 trials with PUEs ranging from 3.2 to 21.4 kg grain per kg P applied.

TABLE 4. Crop rotation effects on wheat grain yield at Kulumsa and Asasa (1994-95)

Contrast^a	Kulumsa		Asasa	
	1994	1995	1994	1995
Rotation^b	***	***	**	***
Dicot vs. cereal (1)	***	***	***	***
2 vs. 3 year (2)	*	**	NS	NS
W#1 vs. W#2 (3)	***	***	*	P<0.1
Fb vs. Rp (4)	*	***	NS	***
1 x 2	P<0.1	NS	NS	NS
2 x 4	NS	NS	NS	NS

1 x 3	*	**	NS	**
3 x 4	NS	*	NS	NS

*, **, ***: Significant at the 5, 1 and 0.1% level, respectively
NS: Not significant
^a See Materials and Methods for complete description of orthogonal contrasts used
^b Main effect with 11 degrees of freedom

Rotation effects on wheat grain yield. The rotation main effect on wheat GY was highly significant in all four trials (Table 2). Upon partitioning of the rotation main effect, seven of the eight single d.f. components (see Materials and Methods) were significant in at least one trial (Table 4). However, the following four components exerted the greatest influence on wheat GY across the four trials:

- in all 4 trials, wheat GY was higher in rotation with dicotyledonous vs. cereal crops, and the GY increments ranged from 29 to 54%;

- in 3 trials, wheat GY was higher in rotation with faba bean vs. rapeseed, and the GY increments ranged from 11 to 31%;

- in all 4 trials, the GY of the first wheat crop after any precursor was higher than the GY of the second wheat crop. The increments ranged from 13 to 48%; and

- in 2 trials, the GY of wheat in 2 year rotations, regardless of break crop, was higher than the mean GY of wheat in 3 year rotations. The increments ranged from 8 to 10%, primarily reflecting the large differential between the first and second crop wheat (i.e., as discussed in the previous component).

The marginally significant interaction between dicot vs. cereal with 2 vs. 3 year rotation at Kulumsa in 1994 (contrast 5 in Table 4) reflected a pronounced decline in mean wheat GY in 3 year rotations with either dicot precursor (i.e., 850 kg ha^-1 for 2 year vs. 736 kg ha^-1 for 3 year), while the 2 and 3 year rotations of wheat with barley did not differ in GY (i.e., 543 and 565 kg ha^-1), but both were significantly lower than the mean GY of wheat in 3 year rotations with dicots. This difference was primarily due to the significant interaction between dicot vs. cereal rotations with W#1 vs. W#2 which was significant in 3 of 4 trials (contrast 7 in Table 4). In all 3 trials, W#1 after either dicot crop was superior in GY to all other permutations. In 2 trials, W#2 after either dicot was superior in GY to W#1 after barley. In 2 trials, W#1 and W#2 after barley did not differ in GY. Across the 3 trials in which significant differences were detected due to this interaction, GY declined by 25% in the second successive wheat crop after either dicot, but showed no change in the second successive wheat crop after barley.

In the Kulumsa 1995 trial, the interaction between W#1 vs. W#2 and faba bean vs. rapeseed was significant (contrast 8 in Table 4). The GY of W#1 after faba bean (5541 kg ha^-1) > W#2 after faba bean (4405 kg ha^-1) > W#1 after rapeseed (3892 kg ha^-1) > W#2 after rapeseed (3422 kg ha^-1). Thus, the interaction was due to a differential rate of decline in GY, resulting from extending cycle length in rotations with faba bean vs. rapeseed: extending cycle length to 3 years reduced wheat GY by 1136 kg ha^-1 (or 21%) in faba bean rotations vs. 470 kg ha^-1 (or 12%) in rapeseed rotations.

Wheat crop parameters and yield components were also significantly affected by the rotation main effect and its orthogonal, single d.f. components in each trial (data not shown). The density of emerged wheat seedlings (i.e., number m-2) and the harvest index of the mature wheat crop were least affected by rotational factors. Crop height was markedly affected by the dicot vs. cereal, W#1 vs. W#2, and faba bean vs. rapeseed contrasts; in each case, crop height was increased by the same factors that exerted a positive effect on wheat grain yield. The number of wheat spikes m-2 was less frequently affected than the number of grains spike^-1 and thousand kernel weight of wheat, which were extremely sensitive to crop rotation, suggesting that the differential effects of the crop rotational systems were manifested after the initiation of wheat stem elongation.

TABLE 5. Wheat grain yield response to precursor crops at Kulumsa and Asasa (1994-1995) as a percent of the yield of continuous wheat

Rotation	Kulumsa		Asasa	
	1994	1995	1994	1995
First year after faba bean	172	165	150	221
Second year after faba bean	106	135	122	169
First year after rapeseed	152	125	156	167
Second year after rapeseed	100	105	127	141

First year after barley	109	107	109	121
Second year after barley	92	104	87	139
Continuous wheat^a	100	100	100	100

^a Index yields = 538, 3262, 1220 and 1473 kg ha^-1, respectively

Cropping sequence effects on wheat GY are summarised in Table 5. The indexed values highlight the superior GY performance of wheat sown immediately after a dicot crop, particularly faba bean - an advantage which markedly diminished in the second consecutive wheat crop. The yield-enhancing effects of rotation with dicots could be due to multiple factors: Tezera *et al.* (1996) demonstrated that, at Kulumsa, wheat in rotation with dicot crops exhibited a lower incidence of yield-reducing root diseases such as take-all (*Gaeumannomyces graminis* var. *tritici*) and eyespot (*Pseudocercosporella herpo-trichoides*); Amanuel *et al.* (1996a) showed that faba bean increased soil nitrate contents and rapeseed decreased soil penetrometer resistance to an extent detectable in the second successive wheat crop; Amanuel *et al.* (1996b) also showed that densities of weedy grass species such as *Avena fatua* and *Setaria pumila* were significantly reduced at Kulumsa in wheat following dicots, particularly faba bean.

In agreement with a previous report (Amanuel *et al.*, 1994), wheat GY in the current study was not significantly enhanced in rotation with barley, although the first year wheat crop exhibited a (non-significant) tendency to be slightly higher than continuous wheat (Table 5).

Thus, as calculated from the values in Table 5, the mean incremental effect on wheat GY (based on the indexed trial yields) was: for faba bean, 77% in the first wheat crop and 33% in the second consecutive wheat crop; for rapeseed, 50% in first wheat and 18% in the second crop; for barley, 12% in first wheat, and 6% in the second wheat crop.

The current results show clearly that rotation with faba bean had a far greater impact on wheat GY than did the addition of 41 or 30 kg N ha^-1 in 1994 and 1995, respectively. Across the 4 trials, the incremental GY due to the high N application rate ranged from 79 to 622 kg ha^-1, while the increment in the first wheat crop after faba bean vis-a-vis continuous wheat ranged from 610 to 2120 kg ha^-1. Yield benefit in cereal-legume rotations beyond that accounted for by the "N fixation effect" has been referred to as "rotation effect" by Franzluebbers *et al.* (1995).

Rotation by nutrient interaction. Although the rotation by N interaction effect (with 11 degrees of freedom) was NS in both seasons at Asasa, several orthogonal components were significant in 1995 (Table 6). Both trials at Kulumsa exhibited significant rotation by N interaction.

TABLE 6. Effects of interaction of crop rotation and fertiliser N application on wheat grain yield at Kulumsa and Asasa (1994-95)

Contrast^a	Kulumsa		Asasa	
	1994	1995	1994	1995
Rotation x N^b	***	**	NS	NS
(Dicot vs. cereal) x N	NS	NS	NS	NS
(2 vs. 3 year) x N	NS	NS	NS	P<0.1
(W1 vs. W2) x N	P<0.1	NS	NS	*
(Fb vs. Rp) x N	***	***	NS	**

*, **, ***: Significant at the 5, 1 and 0.1% level, respectively
NS: Not significant
^a See Materials and Methods for complete description of orthogonal contrasts used
^b Rotation by fertiliser N interaction with 11 degrees of freedom

The interaction effects of N rate with rotation cycle length and with successive wheat crops are shown in Table 7. Wheat GY in 2 year rotations with any precursor crop did not respond to additional N, but the mean GY of wheat in 3 year rotations did respond significantly to additional N: relative to the low N rate, NUE was 11.6 kg grain per kg additional N up to the 60 kg N ha^-1 level. Similarly, in the Asasa 1995 trial (Table 7), there was no response to N in the first wheat crops after any precursor, while the second wheat crops did respond to additional N (with an NUE of 17.8 kg grain per kg N).

TABLE 7. Effects of interaction of N fertiliser application rate with rotational cycle length and successive wheat crops on wheat grain yield (kg ha^-1) at Asasa in 1995

	Cycle length (y)	Wheat crop^a

	2	3	W# 1	W# 2
N fertiliser (kg ha^-1):				
30	2425	2173	2408	1937
60	2487	2520	2568	2472
LSD (P=0.05)	217b		259	

^a First or second wheat crop within 3 year rotational cycles.
^b LSD at P=0.10 level

The interaction between N rate and faba bean vs. rapeseed precursor affected wheat GY in three of the four trials (Table 6). In the two trials of 1995, the GY of wheat in rotations with faba bean (i.e., consisting of both 2 and 3 year cycle lengths) did not respond to an additional 30 kg N ha^-1, while additional N applied to wheat in rapeseed rotations did increase wheat GY (Fig. 1): NUEs were 28.0 and 14.4 kg grain per kg N at Kulumsa and Asasa, respectively. Thus, the reduced N response in wheat after faba bean in the current study is consistent with published reports that cereal GY response to fertiliser N and optimal N application rates are normally reduced following grain legume crops (Hargrove *et al.*, 1983; Narwal *et al.*, 1983; Ladd and Amato, 1985; Franzluebbers *et al.*, 1995).

Figure 1 - The effect of N application rate on wheat grain yield within rotations with faba bean vs. rapeseed, Kulumsa and Asasa, 1995 (bars in each group designated by a unique letter are different at the P<0.05 level).

TABLE 8. Effects of interaction of crop rotation and fertiliser P application on wheat grain yield at Kulumsa and Asasa (1994-95)

Contrast^a	Kulumsa		Asasa	
	1994	1995	1994	1995
Rotation x P^b	*	*	NS	*
(Dicot vs. cereal) x P	NS	NS	NS	*
(2 vs. 3 year) x P	NS	P<0.1	NS	NS
(W1 vs. W2) x P	*	NS	NS	NS
(Fb vs. Rp) x P	NS	NS	NS	**

*, **, ***: Significant at the 5, 1 and 0.1% level, respectively
NS: Not significant
^a See Materials and Methods for complete description of orthogonal contrasts used
^b Rotation by fertiliser P interaction with 11 degrees of freedom

Rotation by P interaction effects on wheat GY were significant in all trials except Asasa in 1994 (Table 8). Wheat GY response to P was not significant in cereal rotations or in the second wheat crop after any precursor crop (Table 9). In contrast, the response to P was significant in dicot rotations and in the first wheat crop after any precursor: PUE was 26.4 and 7.1 kg grain per kg fertiliser P in the two cases, respectively. There was also a differential response to P in dicot vs. cereal rotations and in 2 year vs. 3 year rotations (Fig. 2). Wheat GY response to P was significant in 2 year rotations, exhibiting a PUE of 14.8 kg grain per kg P, but in 3 year rotations mean wheat GY response was non-significant. Comparing response to P in wheat within faba bean vs. rapeseed rotations (Fig. 2) revealed that PUE was much higher in faba bean (38.8 kg grain per kg P) than in rapeseed (14.0 kg grain per kg P) rotations. The enhanced PUE in legume-cereal rotations, consistent with the literature (Sinha *et al.*, 1983), suggests a synergistic effect of legumes on P uptake and utilisation efficiency in a subsequent cereal crop, perhaps as a result of enhanced crop root vigour due to elevated soil N levels and reduced soil pathogen and pest populations.

Figure 2 - The effect of P application rate on wheat grain yield within 3 vs. 2 year rotations and in rotation with faba bean vs. rapeseed, Kulumsa and Asasa, 1995.

TABLE 9. Effects of interaction of P fertiliser application with rotational crops and successive wheat crops on wheat grain yield (kg ha^-1) at Kulumsa in 1994 and Asasa in 1995

	Kulumsa		Asasa	
	Wheat crop^a		Rotational crop	
	W# 1	W# 2	Dicot	Cereal

P fertiliser (kg ha^-1):

0	740	540	2452	1656
20	881	556	2980	1880
LSD (P=0.05)	83		224	

^a First or second wheat crop within 3 year rotational cycles

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CONCLUSIONS

Crop rotation had a marked effect on wheat GY in the four site-season combinations presented in this paper, increasing wheat productivity more than fertiliser N or P. Rotation with dicotyledonous crop species, particularly the faba bean grain legume crop, increased wheat GY in two succeeding crops. Across the four trials, faba bean increased wheat GY by 77% in the first wheat crop and 33% in the second consecutive wheat crop; the corresponding values for rapeseed were 50 and 18%. By comparison, the incremental wheat grain yield after barley was only 12 and 6% for the first and the second consecutive wheat crops, respectively. Crop rotation exhibited beneficial interaction effects with fertiliser N and P on wheat GY. Wheat GY response to fertiliser N was minimal or non-significant after a faba bean break crop, and in the first wheat crop after any precursor crop; P response was greatly enhanced in wheat grown after dicots, particularly faba bean, and in the first wheat crop after any break crop.

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