On-farm Research to Derive Fertilizer Recommendations for Small-Scale Bread Wheat Production
Methodological Issues and Technical Results

Amanuel Gorfu, Asefa Taa, Douglas G. Tanner, and Wilfred Mwangi
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The authors wish to thank the farmers (listed in appendix A) and their families for their cooperation in hosting the on-farm fertilizer trials.

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SUMMARY

On-farm trials were conducted throughout the highlands of Ethiopia to establish zone-specific fertilizer recommendations for bread wheat production under smallholder circumstances. Economically optimum fertilizer levels thus generated differ markedly from the preceding MOA (Ministry of Agriculture) national blanket recommendations and from the recently suggested rate revisions. Compared to the common practice of no application of fertilizer to bread wheat, optimum-level applications increased bread wheat grain yields by 29%–178% across the zones and generated a total rate of return on farmers’ investment in excess of 100%. Alternate recommendations are available for farmers with limited amounts of cash to invest.

Nitrogen tended to decrease soil pH but it increased the density of wild oats, the labor required for handweeding, and the incidence of stripe rust on a susceptible cultivar. Phosphorus also increased the incidence of stripe rust but decreased the density of wild oats, presumably affecting both through an enhancement of crop biomass production. To have a sustainable impact on wheat grain yield, increased fertilizer usage should be accompanied by the provision of other essential farm-level inputs such as herbicides and seed of rust-resistant wheat cultivars.
INTRODUCTION

The highlands of Arsi, Bale, Shewa and Gojam regions account for most of the 250,000 ha of bread wheat (Triticum aestivum) produced annually in Ethiopia. Of this total, smallholders cultivate approximately 190,000 ha under the traditional ox cultivation system; the remainder is produced on mechanized state farms (Amanuel et al. 1990).

Since the early 1970s agricultural research in Ethiopia has focused on the intensification of smallholder bread wheat production in the highland agro-ecological zones (i.e. >2000 m). Currently, bread wheat occupies up to 45% of the total cropped land in highly suitable zones (Chilot et al. 1989). However, mean national wheat yields are generally low, primarily because of the lack of sufficient and timely required modern inputs.

Diagnostic surveys have shown that peasant farmers recognize and identify low soil fertility as one of the major constraints to wheat production (Aleligne and Franzel 1987, Alemayehu and Franzel 1987, Chilot et al. 1989). Wheat is estimated to receive 17% of the annual national fertilizer consumption (Asnakew et al. 1991). However, the Ministry of Agriculture (MOA) currently estimates that 24% of the national wheat crop receives fertilizer. Regionally, the highest fertilizer application on wheat was estimated to be in Arsi—43% (Asnakew et al. 1991); the lowest level was in Bale, where only 15% of the wheat farms received fertilizer. Even in Arsi, farmers apply low rates of fertilizer to bread wheat, seldom exceeding 9 kg N and 23 kg P$_2$O$_5$ ha$^{-1}$ compared to MOA’s blanket recommendation of 41 kg N and 46 kg P$_2$O$_5$ ha$^{-1}$ for wheat in all highland regions (Chilot et al. 1989). Few, if any, farmers apply fertilizer at MOA’s recommended rate, citing both supply and cash constraints. Furthermore, the fertilizer MOA commonly supplies to smallholders throughout Ethiopia is diammonium phosphate (DAP), with an analysis of only 18% N to 46% P$_2$O$_5$. Urea, with 46% N, is less frequently available.

Recently there has been some controversy with regard to optimum fertilizer rates for smallholders. IAR generally utilizes 60 kg N and 60 kg P$_2$O$_5$ ha$^{-1}$ for bread wheat seed multiplication, a recommendation derived from maximum yields obtained in on-station fertilizer trials. IAR has historically disseminated this recommendation to the surrounding farm communities, particularly in Shewa Region, served by Holetta Research Center. In the mid-1980s, MOA initiated a national fertilizer trial program with the intent of generating site-specific recommendations (MOA 1987, 1988, 1989). However, the initial fertilizer trials were often conducted on unrepresentative soils (i.e. fenced sites with a history of fertilization, weed control, and crop rotation differing markedly from the surrounding farms) or were located in zones marginal for bread wheat production. For example, of the 66 trial sites selected in 1988, 39 were situated in Shewa while only 6 were located in Arsi and 3 in Bale (MOA 1989). Although it was claimed that bread wheat is grown on Vertisols in very limited areas, 23 of the 66 trial sites on which the results were reported were located on these soils. As a result, the observations generate questions on how representative the sites were of the national wheat production area.

The Ministry of State Farms Development (MSFD) has generated specific fertilizer recommendations for each of the wheat-growing state farms in Arsi and Bale regions, although they are not necessarily relevant to the smallholder sector (Asnakew et al. 1991). In principle, the MSFD experience supports the concept of generating zone-specific fertilizer recommendations rather than following the national blanket recommendations. A range of potential fertilizer recommendations exists but none were derived under actual peasant farmer management.

This research report summarizes the results of fertilizer trials superimposed on farmer-managed wheat fields in six high-priority agro-ecological zones of bread wheat production, specifically in Arsi, Bale and Gojam regions, as served by the Kulumsa, Sinana and Adet research centers respectively. The principal objectives of these trials were: (1) to determine economically feasible, zone-specific fertilizer recommendations for bread wheat production in the peasant sector, and (2) to evaluate the effect of chemical fertilizers on soil and crop parameters that affect the sustainability of the cropping system.

RESULTS OF DIAGNOSTIC SURVEYS IN THE TARGET ZONES

During 1986 through to 1988, IAR staff members of three research centers situated in wheat and barley production zones conducted informal surveys on farming systems served by their respective centers (Alemayehu and Franzel 1987, Aleligne and Franzel 1987, Chilot et al. 1989). In figure 1, these research centers are indicated on a map showing the major and minor wheat-production areas in...
the Ethiopia highlands. Kulumsa Research Center, located near Asela, serves the major bread wheat-producing zones of the Arsi Region; its subcenters, located at Robe, Bekoji and Asasa, represent a range of altitudinal zones and soil types. Sinana Research Center serves smallholders in Bale Region, while Adet Research Center focuses on farm-level production constraints in the highlands of Gojam. Near Adet, bread wheat is a relatively minor crop at present but is considered of high potential for expansion in this predominantly tef- and barley-producing zone (Aleligne and Franzel 1987).

Kulumsa

The survey in the Kulumsa area indicated that before 1967 farmers neither used nor understood the use of inorganic fertilizers (Chilot et al. 1989). However, as of 1987 almost all farmers were accustomed to fertilizer application on wheat, barley and maize. In fact, most farmers complained of their difficulty in obtaining sufficient quantities of fertilizers through the service cooperatives (SCs) of MOA. The average rate of fertilizer usage on bread wheat was 60 kg DAP ha⁻¹, 10.8 kg N and 27.6 kg P₂O₅ ha⁻¹. Since the proportion of noncereal crops, particularly leguminous species such as faba bean (Vicia faba), had declined over the 1967-1987 period, the authors of this survey were concerned about the declining soil fertility in the wheat- and barley-based farming systems in Arsi. Wheat yields were reported to range between 800 kg ha⁻¹ and 2500 kg ha⁻¹, depending on seasonal climatic fluctuations.

Sinana

The smallholder wheat- and barley-based farming systems in Bale were characterized by lower levels of technology than those in Arsi (Alemayehu and Franzel 1987). Over the last 25 years adoption of released bread wheat cultivars in Ethiopia had been minimal. Similarly, adoption of improved crop management practices such as effective weed control methods (handweeding or herbicide) and fertilizer application had been extremely low. Of the few farmers applying fertilizer to bread wheat, the maximum rate observed was 50 kg DAP ha⁻¹, representing 9 kg N and 23 kg ha⁻¹ P₂O₅. Bread wheat yield levels were reported to range between 700 kg ha⁻¹ and 1500 kg ha⁻¹.

Adet

Of the farmers surveyed, 50% applied fertilizer to at least one crop on their farms, with the rates varying according to the crops. For example, 50% of the tef crop received an average fertilizer rate of 50 kg DAP ha⁻¹, while 37% of the barley crop received a mean rate of 70 kg DAP ha⁻¹. Fertilizer application also varied in terms of soil type—41% of the farmers used DAP on light brown and red soils, while less than 5% applied urea to crops on black soils (i.e. Vertisols). Farmers who did not use fertilizers said their reasons were:

- lack of cash since credit was not available through service cooperatives (SCs)
- inability to purchase desired quantities of fertilizer through SCs
- low profitability of using fertilizers (the farmers’ belief)

TRIAL DESIGN AND METHODOLOGY

Site and soil characteristics

A total of 74 on-farm fertilizer trials were conducted on bread wheat from 1988 to 1990, clustered in six agro-ecological zones situated in Arsi, Bale and Gojam regions (table 1). Mean altitudes ranged between 2200 m and 2780 m, and long-term precipitation means ranged from 620 to 1275 mm yr⁻¹. With the exception of the Asasa sandy loam, all soils exhibited clay content in excess of 40%.

Within each zone, host farmers were initially identified by local extension agents of MOA as being representative bread wheat producers based on their prior yield levels, cropping practices and farm soil types. In the Adet zone, producer cooperatives (PCs) interested in the production of bread wheat were contacted. All selected farmers and PCs expressed willingness to host an on-farm fertilizer trial.

Experimental methods

In 1988 and 1989, eight fertilizer trials were established on bread wheat in each of Asasa, Bekoji, Robe and Gondie zones, and 18 and 20 in Adet and Sinana zones respectively (table 2). In 1990, four additional trials were sown in Robe zone. Of the total of 74 trials sown over the zones, 52 were harvested and included in the subsequent analyses (appendix A); 22 were lost or abandoned because of waterlogging or erosion damage, premature harvest by the host farmer, severe attack by stripe rust (Puccinia striiformis f. sp. tritici), technical errors, or poor emergence.

Individual trials contained four N and four P₂O₅ rates in a complete factorial arrangement. Except
Figure 1. Major and minor wheat-production areas in Ethiopia, indicating IAR research centers conducting on-farm fertilizer trials. Scale – 1:8 000 000
Table 1. Agro-ecological characteristics of the on-farm fertilizer trial sites grouped by zone

<table>
<thead>
<tr>
<th>Zone</th>
<th>Soil group*</th>
<th>pH</th>
<th>Organic matter (%)</th>
<th>N¹ (%)</th>
<th>P¹ (ppm)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Annual rainfall (mm)</th>
<th>Mean altitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bekoji</td>
<td>Ne</td>
<td>5.6</td>
<td>7.3</td>
<td>0.422</td>
<td>17</td>
<td>16.8</td>
<td>34.7</td>
<td>48.5</td>
<td>1050</td>
<td>2780</td>
</tr>
<tr>
<td>Robe</td>
<td>Vp</td>
<td>6.1</td>
<td>4.7</td>
<td>0.220</td>
<td>25</td>
<td>12.2</td>
<td>29.8</td>
<td>58.0</td>
<td>810</td>
<td>2420</td>
</tr>
<tr>
<td>Gondie</td>
<td>Lo</td>
<td>6.1</td>
<td>4.4</td>
<td>0.269</td>
<td>24</td>
<td>21.0</td>
<td>36.3</td>
<td>42.7</td>
<td>820</td>
<td>2200</td>
</tr>
<tr>
<td>Sinana</td>
<td>Lc</td>
<td>6.7</td>
<td>3.6</td>
<td>0.205</td>
<td>26</td>
<td>14.4</td>
<td>24.9</td>
<td>60.7</td>
<td>830</td>
<td>2400</td>
</tr>
<tr>
<td>Asasa</td>
<td>Ck</td>
<td>6.3</td>
<td>5.3</td>
<td>0.304</td>
<td>28</td>
<td>33.3</td>
<td>39.8</td>
<td>26.9</td>
<td>620</td>
<td>2360</td>
</tr>
<tr>
<td>Adet</td>
<td>Ne</td>
<td>5.3</td>
<td>3.7</td>
<td>0.174</td>
<td>18</td>
<td>10.9</td>
<td>28.9</td>
<td>60.2</td>
<td>1275</td>
<td>2240</td>
</tr>
</tbody>
</table>

* FAO/UNESCO soil classifications from 1:2 000 000 scale maps
¹ total soil N and available soil P (Mehlich) at sowing

Table 2. Number of bread wheat on-farm fertilizer trials planted and harvested from 1988 to 1990

<table>
<thead>
<tr>
<th>Zone</th>
<th>1988 Planted</th>
<th>1989 Planted</th>
<th>Total</th>
<th>1988 Harvested</th>
<th>1989 Harvested</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinana</td>
<td>8</td>
<td>12</td>
<td>20</td>
<td>5</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>Adet</td>
<td>10</td>
<td>8</td>
<td>18</td>
<td>8</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>Gondie</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Asasa</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Bekoji</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Robe</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>34</td>
<td>36</td>
<td>70</td>
<td>25</td>
<td>25</td>
<td>50</td>
</tr>
</tbody>
</table>

In 1980, four bread wheat fertilizer trials were planted at Robe, and only two trials were harvested.

for the Adet trials, the nutrient levels used were 0, 20.5, 41 and 82 kg N ha⁻¹ and 0, 23, 46 and 92 kg P₂O₅ ha⁻¹. Low nutrient rates were purposely included to facilitate the determination of alternate recommendations for farmers with different levels of cash to invest. For the Adet trials, the nutrient levels used were 0, 46, 92 and 138 kg ha⁻¹ for both N and P₂O₅.

Host farmers followed their customary and preferred practices for nonexperimental factors such as cropping sequence (most followed the common rotation of wheat after barley), timing and frequency of tillage passes with the local ox plow, and postemergence weed management (none, handweeded once or twice, or herbicide applied). Thus, these superimposed trials exposed the fertilizer intervention to the range of crop management practices existing in each zone. However, since farmers in the Sinana and Adet zones normally do not weed cereal crops other than tef, the researchers in both zones simulated the weed management practice common among wheat producers in Arsi Region—one selective handweeding.

IAR staff laid out the trials, applying preweighed fertilizer treatments on each farmer’s preferred sowing date. The 16 treatments were laid out in a randomized complete block design with two or three replications per site. In 1988, three replications per site were used in all zones except Adet. In 1989, two replications per site were used in all zones in which the 1988 results indicated sufficient homogeneity, namely Sinana, Gondie and Asasa. This modification was implemented to reduce the cost and labor time associated with each trial. At most of the sites, the replications were doubled arrays of eight plots, each to reduce the heterogeneity within replications. Gross plot size was 25 m² except in the Adet zone where it was 20 m². Although trial designs had originally been standardized across the zones, the Adet trial design was later modified during the IAR research proposal review procedure (refer to design standardization under ‘Methodological issues’).

Subsequent to fertilizer application, host farmers immediately broadcast seeds of a released bread wheat cultivar at the recommended seed rate of 150 kg ha⁻¹; the semidwarf cultivar Dashen was used in all zones except the preferred cultivar…
Enkoy was used in Asasa and ET13 in Robe. In 1989, the seed rate for Dashen was increased to 175 kg ha⁻¹ to improve crop stands. The local ox plow was used to incorporate seed and fertilizer. All subsequent field operations prior to harvest were carried out by the host farmers, except at Sinana and Adet where the research staff handweeded the plots.

Urea and triple superphosphate (TSP) were used as N and P₂O₅ sources respectively. In all zones except Adet, N was split applied with one-third broadcast at sowing and two-thirds top-dressed at the mid-tillering stage of wheat. In Adet zone, the complete N dose was applied at sowing. Data were collected prior to harvest on plant height, weed density, including a wild oat (Avena fatua) panicle count at selected sites, days to heading and maturity, and disease incidence. At Adet, labor data were recorded for the handweeding of individual plots.

At crop maturity, a 9-m² area was hand harvested at ground level from each plot (at Adet, a 12-m² net plot was used), and biomass, grain and straw yields were determined. Grain yield was adjusted to 12.5% moisture. Harvest index (HI), thousand-kernel weight (TKW) and hectoliter weight were determined for each plot.

Soil samples were taken from each trial site at sowing to determine soil pH, organic matter content (Walkley and Black 1947), total N content (Bremner 1965) and available P (Mehlich et al. 1962). A site in each of Gondie, Asasa and Bekoji zones plus two sites in the Adet zone were selected for intensive soil sampling (i.e. each plot was sampled) at harvest time to examine the residual effect of fertilizer on soil parameters. The grain and straw samples from each plot at these sites were analyzed for N and P content.

All data were subjected to analysis of variance, first considering individual trials and then grouping together all site-year combinations within each zone. Grain yields in each zone were fitted to response surfaces using least-squares estimation methods. Transformations were considered for wild oat panicle counts and stripe rust scores. However, as the variances of the original data satisfied the requirements for homogeneity and adaptivity, transformation was not necessary. Trends with N and P₂O₅ rates were evaluated using orthogonal contrasts.

The economics of the response of wheat grain yield to fertilizer was studied using partial budget analysis. The partial budget approach is a useful method for evaluating the profitability of a technological innovation; the marginal returns achieved with a new technology are compared to the marginal cost of adopting the technology.

Wheat grain was valued using the 3-year average local market price for the 1988/89–1990/91 period. These prices were ETB 71 per 100 kg of white grain in Bekoji, Robe, Sinana and Gondie zones; ETB 80 per 100 kg of white grain in Adet; and ETB 58 per 100 kg in Asasa for mixed wheat grain.

Average nutrient prices for N and P₂O₅ varied from ETB 1.38 kg⁻¹ to ETB 1.56 kg⁻¹, depending on the source material and based on the 1988/89–1990/91 national market prices for DAP and urea. Straw was not valued because there is no market for it in most zones, and generally peasant farmers in Ethiopia do not sell it.

Other operational costs such as for applying fertilizer, harvesting, threshing, storing and transporting wheat grain were obtained from various secondary sources (Gryseels et al. 1988, MOA 1986, Legesse and Asfaw 1989, Hailu Beyene pers. comm.). The actual costs used for these operations in the partial budget analysis as based on the above sources were fertilizer application 0.36 ETB kg⁻¹ nutrient; harvesting ETB 45 t⁻¹; threshing and storing ETB 27 t⁻¹; transportation by donkey ETB 1.20 per 50 kg. The market prices for fertilizer and wheat were used rather than field prices in calculating net benefit to farmers because of the paucity of data.

Methodological issues

Variatel effects: It is important to recognize that the zone-specific fertilizer recommendations generated by this study may also be specific to the particular bread wheat cultivar used in each zone. At the time of initiating the trial proposals, the cultivar preferred for each zone by IAR's wheat scientists was incorporated as a nonexperimental factor. Subsequent changes in varietal preference, such as the reduction in area of the semidwarf Dashen in zones subject to high levels of stripe rust, may necessitate repeating the on-farm fertilizer trials, particularly where farmers are shifting between semidwarf (Dashen), intermediate height (Enkoy, K6295-4A, ET13), and tall (Wollandi, Israel) bread wheat cultivars.

Seasonal effects: Where sufficient data exist, the climatic patterns of the cropping seasons included in the trial series should be assessed relative to long-term averages. For example, total rainfall in 1988 and 1989 appeared to exceed long-term averages by 8.5% and 33.8% respectively in the Asasa zone; further breakdown of the data indicated, however, that rainfall received during the actual crop growing period (June to October) in 1988
actually exceeded that of 1989 (535 mm in 1988 and 473 mm in 1989). Total rainfall in Robe (Arsi Region) in 1988 and 1989 averaged 30.1% above the long-term average, contributing to the loss of trial sites caused by waterlogging in this Vertisol zone. Sinana experienced pronounced dry spells in 1988 and 1989, contributing to delayed sowing in some seasons, subjecting the crop to late-season drought stress, and to reduced emergence and early-season drought stress in others. When a season is judged to be extremely atypical, it may be necessary to disregard the data and repeat the trial for a further season or year.

Number of replications: As stated previously, the initial trial proposals stipulated three replications per site as a standard in all zones with the exception of Adet. Given the acceptable range of CVs in the Gondie, Asasa and Sinana zones, reflecting a higher degree of soil homogeneity within fields, the number of replications was reduced to two per site to reduce the time and labor cost associated with each trial. This decision represented a compromise between the desire to have maximum precision and the need to streamline on-farm trials—to reflect constraints limiting research workforce, transport and budget.

Seed rate: Based on general experience, it was deemed preferable to fix seed rates at a standard level across the trial sites rather than allow farmers to have unrestricted access to seed, provided by research staff. By fixing this nonexperimental factor at a representative level for wheat-producing smallholders, heterogeneity across sites was minimized.

Weed management practices: In Arsi Region (Gondie, Bekoji, Asasa and Robe zones), where farmers have been exposed to many facets of improved wheat production technology over the past two decades by the extension service, research staff members decided to ask farmers to follow a preferable practice for weed control. Most of the farmers applied a single, partial and selective handweeding; a significant minority applied 2,4-D herbicide for broadleaf weed control; none of the host farmers failed to apply one or the other of these practices. By contrast, farmers in the Bale and Gojam regions have not been exposed to improved wheat crop management practices to the same extent as farmers in the Arsi region, and they verbally stated their intent to ignore weeding of bread wheat as is their custom for their dominant crop, barley. As a consequence, research staff decided to intervene and apply a simulated partial handweeding, as is practiced by peasant wheat farmers in Arsi Region. Thus, the fertilizer responses obtained in the Sinana and Adet zones reflect not just fertilizer application but its combination with improved weed management practice.

Design standardization: Although the proposals for the on-farm fertilizer trials on bread wheat were initially standardized across zones, significant amendments were made during the successive IAR research review meetings at zonal and regional levels. For example, the Adet trial proposal was amended to change plot size, the number of replications per site, and the N and P₂O₅ rates. The most dramatic change was that of requiring the Adet staff to broadcast all N at sowing while the other zones split-applied N with two-thirds top-dressed at mid- to late-tillering to minimize the early flush of weed growth. Currently, new IAR wheat research proposals are reviewed on a crop commodity basis across zones and regions, thereby facilitating standardization of design and methodology.

Determination of economic optima: To establish fertilizer recommendations, standard production function analysis has been widely applied to derive optimal fertilizer rates. Regression analysis is used to fit a suitable response function, and then optimal levels are calculated by setting the marginal productivity of nutrients equal to the ratio of the nutrient and crop prices. In this study, discrete analysis was used because to obtain relevant recommendations for peasant farmers it is felt that the methodology used for the analysis—discrete or continuous—is of secondary importance compared to the experimental design and the price assumptions used. We have made our assumptions more realistic by adjusting costs and benefits to reflect farmers’ circumstances following the procedures outlined by CIMMYT (1988). Byerlee (1980) observed that although regression analysis is useful in smoothing the data and allowing interpolation between points, partial budget analysis of the treatments usually gives very similar results. Byerlee further observed that the realism of cost and yield assumptions used in the analysis is more important than the analytical technique employed.
AGRONOMIC ANALYSIS OF THE RESULTS

Grain yield

Response to fertilizers varied markedly amongst the zones, but it was relatively consistent within zones as is apparent upon examination of the response in the individual site-year combinations (appendix A). Overall, the Bekoji, Asasa and Sinana trials exhibited greater yield response to P2O5 than to N, while the Robe and Gondie trials responded more to N. In the Adet zone, both N and P2O5 were highly significant. Trial mean yields ranged from 626 kg ha⁻¹ (in Robe) to 4441 kg ha⁻¹ (in Asasa), while CVs ranged from 6.2% to 48.0%.

Considering all 52 trials, responses were fairly evenly divided amongst response to N only, to P2O5 only, to both N and P2O5 and to neither of the fertilizers (table 3). N by P2O5 interaction was significant in only five of the trials, consistent with the previous study (Amanuel et al. 1990).

Trial data were grouped together within zones and analyzed according to a multilocation design (table 4). Site × nutrient interactions were nonsignificant in most cases as was N × P interaction, while ‘sites’ (site-year combinations) were significant in each zone. Zonally, mean yields ranged from 1553 kg ha⁻¹ to 3752 kg ha⁻¹, and CVs ranged from 16.3% to 26.0%.

On Nitosols of the Bekoji zone, P response was highly significant and linear within the range of P levels included in this trial. Site × P interaction arose from the nonsignificant response to P at two of the seven sites. Only one site exhibited a significant response to N.

In the Gondie zone, response to both N and P2O5 was highly significant; the quadratic component for N was significant at the 10% level. All interaction terms were nonsignificant.

In the Asasa zone, site × N and site × P2O5 interactions were significant, primarily because of unusually heavy and well-distributed rainfall during the 1988 growing season, affecting both nutrient response and yield levels; mean grain yields were 4311 kg ha⁻¹ in 1988 and 2785 kg ha⁻¹ in 1989—much higher than the previously recorded grain yields. However, separate analysis of the 1988 and 1989 trial data illustrated that P2O5 response was highly significant in both years although varying in degree, while N response was significant only in 1988 because of a highly significant response at one site.

In the Robe zone, N response was highly significant and linear, while P response was lower and naturally quadratic. This result is not surprising when considering that the zone consists primarily of Vertisols, which are prone to waterlogging.

The low response to fertilizer at Sinana is probably a consequence of low rainfall in this zone: the total annual rainfall of 830 mm is distributed almost equally between two growing seasons. The trials were in fact distributed over four growing seasons in two years. By comparison, the other zones included in this study experienced a more unimodal distribution of rainfall. In the Sinana zone, all interaction terms were nonsignificant.

The combined analysis of the data from the Adet zone proved more difficult to interpret as all interaction terms were highly significant. Partial resolution was achieved by grouping the data into two target groups: one subset consisted of trials with check yields >1 t ha⁻¹ (four sites in Adet-1) and another subset comprised trials with check yields <1 t ha⁻¹ (nine sites in Adet-2). Soils of the

---

Table 3. Summary of fertilizer response characteristics by zone

<table>
<thead>
<tr>
<th>Number of sites exhibiting</th>
<th>Bekoji</th>
<th>Gondie</th>
<th>Asasa</th>
<th>Robe</th>
<th>Sinana</th>
<th>Adet</th>
<th>Total</th>
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<tr>
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<td>-</td>
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<td>4</td>
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<tr>
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<td>4</td>
<td>-</td>
<td>3</td>
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<td>11</td>
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<td>1</td>
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<td>but no N × P interaction</td>
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<tr>
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<td>-</td>
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<tr>
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<td>2</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td>11</td>
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<tr>
<td>Total</td>
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<td>11</td>
<td>6</td>
<td>11</td>
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Table 4. Results of combined analyses of variance for grain yield with sites grouped within each recommendation domain

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<th>Robe</th>
<th>Sinana</th>
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<td>***</td>
<td>***</td>
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<td>***</td>
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<td>***</td>
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</tr>
<tr>
<td>linear (Nl)</td>
<td>ns</td>
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<td>*</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>quadratic (Nq)</td>
<td>***</td>
<td>p&lt;0.1</td>
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<td>ns</td>
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<td></td>
</tr>
<tr>
<td>Phosphorus (P)</td>
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<td>***</td>
<td>***</td>
<td>p&lt;0.1</td>
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</tr>
<tr>
<td>linear (Pl)</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>p&lt;0.1</td>
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<tr>
<td>quadratic (Pq)</td>
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<td>ns</td>
<td>ns</td>
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<tr>
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<tr>
<td>N x S</td>
<td>ns</td>
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<td>ns</td>
<td></td>
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<tr>
<td>P x S</td>
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<td>*</td>
<td>ns</td>
<td></td>
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<tr>
<td>N x P x S</td>
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<td>ns</td>
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</table>

Mean (kg ha⁻¹) 1996 2882 3752 1848 1573 2811 1553
CV (%) 24.9 16.3 17.5 26.0 25.5 20.2 24.0
Check yield (kg ha⁻¹) 1495 2259 3372 1334 1241 1846 547

*, **, *** indicate significance at the 5, 1 and 0.1% levels respectively
ns = not significant

Adet zone, which receives the highest annual rainfall and exhibits low levels of soil pH, N, organic matter, and available P (table 1), have been depleted over a long history of human settlement and cultivation in northwestern Ethiopia. For the Adet-2 sites, grain yield responded linearly up to the maximum levels of fertilizer included in the trial (i.e. 138 kg N and 138 kg P₂O₅ ha⁻¹), while the high-yielding sites of Adet-1 exhibited a quadratic response to both nutrients.

Fertilizer response curves were estimated by regression analysis of the mean grain yields for the 16 N x P treatments for each zone. Throughout the analysis, the basic strategy was to include all components in the initial regression followed by the use of appropriate F-tests to successively eliminate all nonsignificant (p < 0.1) regression terms. All final regression equations (table 5) were highly significant with R² values, varying from 0.816 to 0.966. Consistent with the analyses of variance, quadratic components for N and P₂O₅ were seldom significant. This linearity of response is a consequence of deliberate selections of low nutrient rates for this trial so as to facilitate the identification of economic optima for peasant farmers.

Biomass yield

In general terms, biomass yields were increased by both N and P in all zones recording data for this parameter (appendix B), while interaction terms were largely nonsignificant with the exception of the Adet zone. In the Robe zone, biomass yield responded only to N; in the Sinana zone, no response to either of the nutrients was apparent. In the Bekoji zone in 1989 biomass responded only to P.

Straw yield

Straw yields followed the same general trends as biomass yields except that responses to N tended to be more pronounced than to P (appendix C). Straw yields in Adet appeared very low. In the other zones, straw yields ranged from 4221 kg ha⁻¹ to 7865 kg ha⁻¹.

Harvest index

Surprisingly, harvest index (HI) responded significantly only to nutrient rates in five of the nine grouped data sets (appendix D). In every case
Table 5. Coefficients for best fit regression equations of mean grain yield ($Y$) on levels of applied N and P within each recommendation domain

<table>
<thead>
<tr>
<th></th>
<th>Bekoji</th>
<th>Gondie</th>
<th>Asasa</th>
<th>Robe</th>
<th>Sinana</th>
<th>Adet-1</th>
<th>Adet-2</th>
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<td>$a$</td>
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<td>$b_1$</td>
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<td>16.929</td>
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<td>3.834</td>
<td>11.385</td>
<td>7.675</td>
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<td>$b_4$</td>
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<td>-0.066</td>
<td></td>
<td>$P&lt;0.1$</td>
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</tr>
<tr>
<td>$b_5$</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.061</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.903</td>
<td>0.949</td>
<td>0.816</td>
<td>0.906</td>
<td>0.938</td>
<td>0.883</td>
<td>0.966</td>
</tr>
</tbody>
</table>

where there was a significant effect of nutrient, N reduced HI while P increased HI. (In the Gondie zone in 1989, HI was 29.1% at 0 and 33.3% at 92 kg P₂O₅ ha⁻¹.) The HI values reported for Adet appeared suspect, suggesting that wheat stems were not cut at ground level during the harvest.

Plant height

Plant height was significantly increased by higher nutrient rates in all of the grouped data sets (appendix E). On a zonal basis, the height of the semi-dwarf cultivar Dashen varied from 66.7 cm at Sinana up to 91.4 cm at Gondie in 1988. ET 13 at Robe averaged 94.1 cm, while Enkoy at Asasa reached 106.2 cm in 1988 and 94.8 cm in 1989. In five groupings, height increased significantly in response to both N and P, while in three only P affected height, and in one only N affected it.

Days to heading

Days to heading (DTH) of wheat was affected by nutrient rates in four out of the seven grouped data sets (appendix F). However, the responses varied dramatically. In Gondie in both 1988 and 1989, N increased DTH by an average of 2 days and P by 1 day. In Asasa in 1989, P decreased DTH by 4 days, while in Robe in 1990 N decreased DTH by 4 days.

Days to maturity

Maturity was affected by nutrient rates in three of the six groupings reported (appendix G). In every case, DTM was reduced by higher nutrient rates—by P in Asasa and Robe in 1989, and by N and P in Robe in 1990.

Hectoliter weight

In 1989, N reduced hectoliter weight (HLW) by 1.6 kg hl⁻¹ and 2 kg hl⁻¹ at Gondie and Asasa respectively (appendix H); P decreased HLW by 0.7 kg hl⁻¹ at Gondie and 0.9 kg hl⁻¹ at Robe yet increased HLW by 1.3 kg hl⁻¹ in Asasa.

Thousand-kernel weight

Thousand-kernel weight (TKW) was affected by nutrient rates in five out of nine grouped data sets (appendix I). N increased TKW at Robe by 1.6 g in 1989 and 1.7 g in 1990; it decreased TKW by 2.3 g in 1989 and 1.9 g in 1989 at Asasa and by 3.0 g in 1988 at Bekoji. P increased TKW by 1.3 g in 1988 and 1.4 g in 1989 at Asasa, and by 2.3 g in 1990 at Robe.
ECONOMIC ANALYSIS OF THE RESULTS

To recommend technologies capable of improving farmers’ income, it is important to consider a realistic estimate of net benefit rather than yield alone. Thus an economic analysis (partial budget) was conducted for the results from each zone or target group. Two partial budgets were done for each zone based on the range of nutrient prices encountered in Ethiopia, ETB 1.38 and ETB 1.56 per kilogram of nutrients.

Yields were adjusted downward by 20% for Bekoji, Robe, Sinana, Gondie and Asasa zones to more closely reflect yields under farmers’ harvesting, threshing and other management practices; for the two Adet target groups, yields were adjusted downward by 30%, because researchers were more involved in managing the trials in the Adet zone than in the other zones.

Dominance analysis was carried out by first listing the treatments in order of increasing variable costs. Any treatment having a benefit less than or equal to that of a treatment with a lower cost is said to be dominated. Dominated treatments were eliminated from further consideration.

Analysis of marginal rate of return (MRR) was then undertaken in each zone for the nondominated treatments. The MRRs were compared with the minimum acceptable rate of return (MARR), which was assumed to be 100%, to select the most profitable treatment to be recommended to farmers.

Experience and empirical evidence have shown that in many situations the minimum rate of return acceptable to farmers lies between 50% and 100% (CIMMYT 1988). Given the situation of peasant farmers in Ethiopia, lacking agricultural credit, with limited availability of fertilizers in some regions, and lacking experience in the use of fertilizer, a MARR of 100% is realistic.

Sensitivity analysis was also conducted to determine the stability of the recommended treatments. Recent price data for fertilizers imported by the government of Ethiopia show that the farmers’ fertilizer price is being subsidized by 23% for P2O5 and 28% for N per kilogram (ULG Consultants Ltd. 1989). In conducting sensitivity analysis, these subsidies were removed and the price of nutrients was increased to ETB 1.70 and ETB 2 per kilogram for N.

The results of the partial budget analysis for each zone are discussed as follows.

Bekoji zone

Partial budgets for the Bekoji zone are shown in tables 6 and 7. The highest net benefits (ETB 1025 and 1008 ha−1) were obtained from treatment 0–92. Table 8 presents the analysis of MRR, using a nutrient price of ETB 1.38 kg⁻¹; the most acceptable treatment, given a MARR of 100%, was 0–46 (167% MRR). When a nutrient price of ETB 1.56 kg⁻¹ was used, then 0–46 remained the most profitable treatment. Results of the sensitivity analysis are shown in table 9. When the price of P2O5 was increased from ETB 1.38 kg⁻¹ to ETB 1.70 kg⁻¹, treatment 0–46 still remained the most profitable. Thus it appears that a recommended fertilizer rate for the Bekoji zone of 0–46 would be stable within the range of fertilizer prices used in this study.

Robe zone

Partial budgets for the Robe zone are given in tables 10 and 11. The highest net benefits (ETB 1069 and 1046) were obtained from treatment 82–46. Table 12 gives the analysis of MRR. When a nutrient price of ETB 1.38 kg⁻¹ was used, the most profitable treatment was 41–0 (205% MRR). The same held true when a nutrient price of ETB 1.56 kg⁻¹ was used. Results of sensitivity analysis are given in table 13. Treatment 41–0 remained the most profitable when nutrient prices were increased to ETB 1.70 and 2.00 kg⁻¹ for P2O5 and N respectively. Thus this treatment is fairly stable and should be recommended to farmers in the Robe zone.

Sinana zone

Partial budgets for the Sinana zone are given in tables 14 and 15. The highest net benefits (ETB 708 and 699 ha−1) were obtained from treatment 0–92. Table 16 presents the analysis of MRR. Treatment 0–46 gave MRR of 92% (which is below the MARR of 100%). Hence, in this zone, the use of fertilizer did not appear to be profitable and the check treatment (0–0) would be recommended. An increase in nutrient price to ETB 1.7 kg⁻¹ of P2O5 would reduce the MRR for 0–46 to 68%.

However, it is important to recall the discussion of seasonal effects and cultivar effects in the section on methodological issues. The trials in Sinana zone had been conducted using the stripe rust-susceptible cultivar Dashen, and the 1988 and 1989 seasons experienced several pronounced dry spells. It may be advisable to repeat the fertilizer trials using an adapted cultivar such as ET13 and for several more seasons before finalizing the fertilizer recommendation for the Sinana zone.
Table 6. Partial budget for wheat fertilizer trials at Bekoji*

<table>
<thead>
<tr>
<th>Nutrient rates (kg N/P/O ha(^{-1}))</th>
<th>Yield (kg ha(^{-1}))</th>
<th>Adjusted yield (20%) (kg ha(^{-1}))</th>
<th>Gross benefit (ETB ha(^{-1}))</th>
<th>Fertilizer cost (ETB ha(^{-1}))</th>
<th>Cost of application (ETB ha(^{-1}))</th>
<th>Harvesting and storing (ETB ha(^{-1}))</th>
<th>Threshing (ETB ha(^{-1}))</th>
<th>Transport (ETB ha(^{-1}))</th>
<th>Total variable cost (ETB ha(^{-1}))</th>
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</table>

* using a nutrient cost of ETB 1.38 kg\(^{-1}\)

Table 7. Partial budget for wheat fertilizer trials at Bekoji*

<table>
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<tr>
<th>Nutrient rates (kg N/P/O ha(^{-1}))</th>
<th>Yield (kg ha(^{-1}))</th>
<th>Adjusted yield (20%) (kg ha(^{-1}))</th>
<th>Gross benefit (ETB ha(^{-1}))</th>
<th>Fertilizer cost (ETB ha(^{-1}))</th>
<th>Cost of application (ETB ha(^{-1}))</th>
<th>Harvesting and storing (ETB ha(^{-1}))</th>
<th>Threshing (ETB ha(^{-1}))</th>
<th>Transport (ETB ha(^{-1}))</th>
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* using a nutrient cost of ETB 1.56 kg\(^{-1}\)

**Gondie zone**

Partial budgets for this zone are shown in tables 17 and 18. Treatment 82-23 gave the highest net benefits (ETB 1499 and 1480 ha\(^{-1}\)). Table 19 presents the analysis of MRR. When a nutrient price of ETB 1.38 kg\(^{-1}\) was used, the most profitable treatment was 41-0 (202% MRR). It was the same when a nutrient price of ETB 1.56 kg\(^{-1}\) was used. Results of sensitivity analysis are given in table 20. Treatment 41-0 remained the most profitable when nutrient price increased to ETB 1.70 and 2 kg\(^{-1}\) for P\(_2\)O\(_5\) and N respectively. This treatment appears fairly stable and should be recommended to farmers in the Gondie zone.

**Asasa zone**

Partial budgets for the Asasa zone are shown in tables 21 and 22. Treatment 20.5-92 gave the highest net benefits (ETB 1524 and 1503 ETB ha\(^{-1}\)). Table 23 presents the analysis of MRR. When a
Table 8. Marginal analysis for the nondominated treatments at Bekoji

<table>
<thead>
<tr>
<th>N/P/0₃ (kg ha⁻¹)</th>
<th>Variable costs (ETB ha⁻¹)</th>
<th>Marginal costs (ETB ha⁻¹)</th>
<th>Net benefit (ETB ha⁻¹)</th>
<th>Marginal net benefit (ETB ha⁻¹)</th>
<th>Marginal rate of return</th>
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Table 9. Sensitivity analysis for the nondominated treatments at Bekoji

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<th>N/P/0₃ (kg ha⁻¹)</th>
<th>Variable costs (ETB ha⁻¹)</th>
<th>Marginal costs (ETB ha⁻¹)</th>
<th>Net benefit (ETB ha⁻¹)</th>
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<th>Marginal rate of return</th>
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Table 10. Partial budget for wheat fertilizer trials at Robe*

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<tr>
<th>Nutrient rates (kg N/P/0₃ ha⁻¹)</th>
<th>Yield (kg ha⁻¹)</th>
<th>Adjusted yield (20%)</th>
<th>Gross benefit (ETB ha⁻¹)</th>
<th>Fertilizer cost (ETB ha⁻¹)</th>
<th>Cost of application (ETB ha⁻¹)</th>
<th>Harvesting and storing (ETB ha⁻¹)</th>
<th>Transport (ETB ha⁻¹)</th>
<th>Total variable cost (ETB ha⁻¹)</th>
<th>Net benefit (ETB ha⁻¹)</th>
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* using a nutrient cost of ETB 1.38 kg⁻¹
Table 11. Partial budget for wheat fertilizer trials at Robe

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<th>Adjusted yield (kg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Gross benefit (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Fertilizer cost (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Cost of application (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Harvesting and storing (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Transport variable cost (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
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* using a nutrient cost of ETB 1.56 kg<sup>-1</sup>

Table 12. Marginal analysis for the nondominated treatments at Robe

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<th>N/P&lt;sub&gt;20&lt;/sub&gt; (kg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Variable costs (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Marginal costs (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Net benefit (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Marginal net benefit (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Marginal rate of return</th>
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Table 13. Sensitivity analysis for the nondominated treatments at Robe

<table>
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<th>N/P&lt;sub&gt;20&lt;/sub&gt; (kg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Variable costs (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Marginal costs (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Net benefit (ETB ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
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nutrient price of ETB 1.38 kg<sup>-1</sup> was used, the check treatment (0-0) would be recommended as the others gave MRRs below 100%, which may not be acceptable to farmers. It would be the same for any nutrient price above ETB 1.38 kg<sup>-1</sup>. Thus in the Asasa zone, nonuse of fertilizer would be the recommended practice, given current wheat and nutrient prices. It should be noted that the grain price used in Asasa was lower than in the other zones because of the preference for the cultivar Enkoy in this zone. Enkoy has small, red seeds which command a lower price on the local market. Further-
Table 14. Partial budget for wheat fertilizer trials at Sinana*

<table>
<thead>
<tr>
<th>Nutrient rates (kg N/P,O kg ha⁻¹)</th>
<th>Yield (kg ha⁻¹)</th>
<th>Adjusted yield (20%) (kg ha⁻¹)</th>
<th>Gross benefit (ETB ha⁻¹)</th>
<th>Fertilizer cost (ETB ha⁻¹)</th>
<th>Cost of application (ETB ha⁻¹)</th>
<th>Harvesting and storing (ETB ha⁻¹)</th>
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* using a nutrient cost of ETB 1.38 kg⁻¹

Table 15. Partial budget for wheat fertilizer trials at Sinana*

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<th>Yield (kg ha⁻¹)</th>
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<th>Gross benefit (ETB ha⁻¹)</th>
<th>Fertilizer cost (ETB ha⁻¹)</th>
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* using a nutrient cost of ETB 1.56 kg⁻¹

Table 16. Marginal analysis for the nondominated treatments at Sinana

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<th>N/P,O (kg ha⁻¹)</th>
<th>Variable cost (ETB ha⁻¹)</th>
<th>Marginal costs (ETB ha⁻¹)</th>
<th>Net benefit (ETB ha⁻¹)</th>
<th>Marginal net benefit (ETB ha⁻¹)</th>
<th>Marginal rate of return</th>
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Table 17. Partial budget for wheat fertilizer trials at Gondie*

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* using a nutrient cost of ETB 1.38 kg⁻¹

Table 18. Partial budget for wheat fertilizer trials at Gondie*

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<th>Adjusted yield (20%) (kg ha⁻¹)</th>
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* using a nutrient cost of ETB 1.56 kg⁻¹

more, the 1988 and 1989 seasons experienced higher than average precipitation. It may be necessary to repeat the fertilizer trials in the Asasa zone in the future.

Adet-1 target group

Partial budgets for the Adet-1 target group are shown in tables 24 and 25. Treatment 92-46 gave highest net benefits (ETB 1456 and 1431 ha⁻¹).

Table 26 presents the analysis of MRR. When a nutrient price of ETB 1.38 kg⁻¹ was used, treatment 92-46 was the most profitable (153% MRR). The same held true when a nutrient price of ETB 1.56 kg⁻¹ was used. Table 27 gives the sensitivity analysis results. When the nutrient price was increased to ETB 1.70 for P₂O₅ and ETB 2.00 kg⁻¹ N, treatment 92-46 remained the most profitable. Thus, this treatment should be recommended to farmers in the Adet-1 target group.
Table 19. Marginal analysis for the nondominated treatments at Gondie

<table>
<thead>
<tr>
<th>N/P₂O₅ (kg ha⁻¹)</th>
<th>Variable cost (ETB ha⁻¹)</th>
<th>Marginal costs (ETB ha⁻¹)</th>
<th>Net benefit (ETB ha⁻¹)</th>
<th>Marginal net benefit (ETB ha⁻¹)</th>
<th>Marginal rate of return</th>
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Table 20. Sensitivity analysis for the nondominated treatments at Gondie

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<th>Variable cost (ETB ha⁻¹)</th>
<th>Marginal costs (ETB ha⁻¹)</th>
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Table 21. Partial budget for fertilizer trials at Asasa*

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* using a nutrient cost of ETB 1.38 kg⁻¹
**Table 22. Partial budget of fertilizer trials at Asasa**

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<th>Nutrient rates (kg N/P₂O₅ ha⁻¹)</th>
<th>Yield (kg ha⁻¹)</th>
<th>Adjusted yield (20%) (kg ha⁻¹)</th>
<th>Gross benefit (ETB ha⁻¹)</th>
<th>Fertilizer cost (ETB ha⁻¹)</th>
<th>Cost of application (ETB ha⁻¹)</th>
<th>Harvesting and storing (ETB ha⁻¹)</th>
<th>Transport (ETB ha⁻¹)</th>
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* using a nutrient cost of ETB 1.56 kg⁻¹

**Table 23. Marginal analysis for the nondominated treatments at Asasa**

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<th>N/P₂O₅ (kg ha⁻¹)</th>
<th>Cost (ETB ha⁻¹)</th>
<th>Marginal costs (ETB ha⁻¹)</th>
<th>Net benefit (ETB ha⁻¹)</th>
<th>Marginal net benefit (ETB ha⁻¹)</th>
<th>Marginal rate of return</th>
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**Table 24. Partial budget for wheat fertilizer trials for the Adet-1 target group**

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<th>Nutrient rates (kg N/P₂O₅ ha⁻¹)</th>
<th>Yield (kg ha⁻¹)</th>
<th>Adjusted yield (20%) (kg ha⁻¹)</th>
<th>Gross benefit (ETB ha⁻¹)</th>
<th>Fertilizer cost (ETB ha⁻¹)</th>
<th>Cost of application (ETB ha⁻¹)</th>
<th>Harvesting and storing (ETB ha⁻¹)</th>
<th>Transport (ETB ha⁻¹)</th>
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* using a nutrient cost of ETB 1.38 kg⁻¹
Adet-2 target group

Partial budgets for the Adet-2 target group are shown in tables 28 and 29. Treatment 138-138 gave highest net benefits (ETB 921 and 871 ha⁻¹). Table 30 presents the analysis of MRR. When a nutrient price of ETB 1.38 kg⁻¹ was used, treatment 92-46 was the most profitable (130% MRR), and the same held true when a nutrient price of ETB 1.56 kg⁻¹ was used. Table 31 presents results of the sensitivity analysis. When the nutrient prices increased to ETB 1.70 kg⁻¹ for P₂O₅ and 2 kg⁻¹ for N, the check treatment (0-0) would be recommended because the MRR of 92-46 was below 100%. Thus, the recommendation for farmers in the Adet-2 target group is treatment 92-46 as long as the nutrient price does not increase above ETB 1.56 kg⁻¹. If the subsidy is removed and the nutrient price increases to ETB 1.70 kg⁻¹ for P₂O₅ and ETB 2.00 kg⁻¹ for N, then nonuse of fertilizer could be recommended for farmers in the Adet-2 target group.

Summary of economic analysis

The zone-specific nutrient rate recommendations are summarized in table 32. Specific comments for each zone in the preceding subsections should be noted, particularly concerning the results obtained for the Sinana and Asasa zones.

The nutrient rates, producing the highest net benefit in each zone, resulted in increases in grain production, ranging from 32% up to 305% relative to the control treatment (0-0). Based on the price assumptions stated in this analysis, all of these treatments were profitable to the farmers. However, several of these treatments were conservatively considered to be suboptimal for peasant farmers as the associated MRR was often less than 100%. Those nutrient rates determined to satisfy this criterion increased grain yields relative to the control treatment by from 29% to 178%.

Recommendations under cash constraints

Using the results of the partial budget analysis, it is also possible to derive appropriate zone-specific fertilizer recommendations for farmers with various amounts of cash to invest. For example, from figure 2, it is apparent that farmers with cash constraints in the Adet-1 target group can profitably apply fertilizer N at rates up to 46 kg ha⁻¹; at this level, the marginal rate of return would be 168% on an investment of ETB 242 ha⁻¹. An intermediate investment level should be focused on 46-46, while farmers with no cash constraint economic optimum rate of 92 kg N and 46 kg P₂O₅ ha⁻¹, having an MRR of 152% on the additional investment of ETB 229 ha⁻¹.

Figure 2. Net benefit curve for Adet-1 fertilizer trials (dominated treatments excluded).
Table 25. Partial budget for wheat fertilizer trials for the Adet-1 target group

<table>
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<th>Nutrient rates (kg N/P2O5 ha⁻¹)</th>
<th>Yield (kg ha⁻¹)</th>
<th>Adjusted yield (20%)</th>
<th>Gross benefit (ETB ha⁻¹)</th>
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<th>Cost of application (ETB ha⁻¹)</th>
<th>Threshing and storing (ETB ha⁻¹)</th>
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<td>62</td>
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<td>2578</td>
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<td>110</td>
<td>66</td>
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<td>677</td>
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<td>2572</td>
<td>2058</td>
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<td>99</td>
<td>116</td>
<td>69</td>
<td>62</td>
<td>777</td>
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</tbody>
</table>

* using a nutrient cost of ETB 1.56 kg⁻¹

Table 26. Marginal analysis for the nondominated treatments for the Adet-1 target group

<table>
<thead>
<tr>
<th>N/P2O5 (kg ha⁻¹)</th>
<th>Variable cost (ETB ha⁻¹)</th>
<th>Marginal costs (ETB ha⁻¹)</th>
<th>Net benefit (ETB ha⁻¹)</th>
<th>Marginal net benefit (ETB ha⁻¹)</th>
<th>Marginal rate of return</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0</td>
<td>124</td>
<td>118</td>
<td>910</td>
<td>198</td>
<td>168%</td>
</tr>
<tr>
<td>46-0</td>
<td>242</td>
<td>114</td>
<td>1108</td>
<td>172</td>
<td>151%</td>
</tr>
<tr>
<td>46-46</td>
<td>356</td>
<td>115</td>
<td>1280</td>
<td>176</td>
<td>153%</td>
</tr>
<tr>
<td>92-46</td>
<td>471</td>
<td></td>
<td>1456</td>
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<td></td>
</tr>
</tbody>
</table>

Table 27. Sensitivity analysis for the nondominated treatments for the Adet-1 target group

<table>
<thead>
<tr>
<th>N/P2O5 (kg ha⁻¹)</th>
<th>Variable cost (ETB ha⁻¹)</th>
<th>Marginal costs (ETB ha⁻¹)</th>
<th>Net benefit (ETB ha⁻¹)</th>
<th>Marginal net benefit (ETB ha⁻¹)</th>
<th>Marginal rate of return</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0</td>
<td>124</td>
<td>133</td>
<td>910</td>
<td>183</td>
<td>138%</td>
</tr>
<tr>
<td>46-0</td>
<td>257</td>
<td>128</td>
<td>1093</td>
<td>158</td>
<td>123%</td>
</tr>
<tr>
<td>46-46</td>
<td>385</td>
<td>131</td>
<td>1251</td>
<td>161</td>
<td>123%</td>
</tr>
<tr>
<td>92-46</td>
<td>516</td>
<td></td>
<td>1412</td>
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</table>
Table 28. Partial budget for wheat fertilizer trials for the Adet-2 target group*  

<table>
<thead>
<tr>
<th>Nutrient rates</th>
<th>Yield (kg ha(^{-1}))</th>
<th>Adjusted yield (20%) (kg ha(^{-1}))</th>
<th>Gross benefit (ETB ha(^{-1}))</th>
<th>Fertilizer cost (ETB ha(^{-1}))</th>
<th>Cost of application (ETB ha(^{-1}))</th>
<th>Harvesting and storing (ETB ha(^{-1}))</th>
<th>Transport variable cost (ETB ha(^{-1}))</th>
<th>Total variable cost (ETB ha(^{-1}))</th>
<th>Net benefit (ETB ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0</td>
<td>703</td>
<td>492</td>
<td>394</td>
<td>0</td>
<td>0</td>
<td>22</td>
<td>13</td>
<td>12</td>
<td>47</td>
</tr>
<tr>
<td>0-23</td>
<td>779</td>
<td>545</td>
<td>436</td>
<td>63</td>
<td>17</td>
<td>25</td>
<td>15</td>
<td>13</td>
<td>133</td>
</tr>
<tr>
<td>0-46</td>
<td>693</td>
<td>485</td>
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<td>12</td>
<td>207</td>
</tr>
<tr>
<td>0-92</td>
<td>811</td>
<td>568</td>
<td>454</td>
<td>190</td>
<td>50</td>
<td>26</td>
<td>16</td>
<td>14</td>
<td>295</td>
</tr>
<tr>
<td>20.5-0</td>
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<td>588</td>
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<td>876</td>
<td>701</td>
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<td>244</td>
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<td>66</td>
<td>45</td>
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<td>24</td>
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<tr>
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<td>41-23</td>
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<tr>
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<td>55</td>
<td>33</td>
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<tr>
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<td>1593</td>
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<td>99</td>
<td>90</td>
<td>54</td>
<td>48</td>
<td>672</td>
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</table>

* using a nutrient cost of ETB 1.38 kg\(^{-1}\)

Table 29. Partial budget for wheat fertilizer trials for the Adet-2 target group*  

<table>
<thead>
<tr>
<th>Nutrient rates</th>
<th>Yield (kg ha(^{-1}))</th>
<th>Adjusted yield (20%) (kg ha(^{-1}))</th>
<th>Gross benefit (ETB ha(^{-1}))</th>
<th>Fertilizer cost (ETB ha(^{-1}))</th>
<th>Cost of application (ETB ha(^{-1}))</th>
<th>Harvesting and storing (ETB ha(^{-1}))</th>
<th>Transport variable cost (ETB ha(^{-1}))</th>
<th>Total variable cost (ETB ha(^{-1}))</th>
<th>Net benefit (ETB ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0</td>
<td>703</td>
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<td>394</td>
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<td>13</td>
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<tr>
<td>0-23</td>
<td>779</td>
<td>545</td>
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<td>81</td>
<td>49</td>
<td>43</td>
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<td>1223</td>
<td>978</td>
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<td>33</td>
<td>29</td>
<td>357</td>
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<tr>
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<td>1541</td>
<td>1233</td>
<td>254</td>
<td>66</td>
<td>69</td>
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<td>37</td>
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<td>573</td>
</tr>
<tr>
<td>82-92</td>
<td>2844</td>
<td>1991</td>
<td>1593</td>
<td>381</td>
<td>99</td>
<td>90</td>
<td>54</td>
<td>48</td>
<td>672</td>
</tr>
</tbody>
</table>

* using a nutrient cost of ETB 1.56 kg\(^{-1}\)

Table 30. Marginal analysis for the nondominated treatments for the Adet-2 target group  

<table>
<thead>
<tr>
<th>N/P,05O, ha(^{-1})</th>
<th>Variable cost (ETB ha(^{-1}))</th>
<th>Marginal costs (ETB ha(^{-1}))</th>
<th>Net benefit (ETB ha(^{-1}))</th>
<th>Marginal net benefit (ETB ha(^{-1}))</th>
<th>Marginal rate of return</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0</td>
<td>47</td>
<td>213</td>
<td>347</td>
<td>231</td>
<td>108%</td>
</tr>
<tr>
<td>92-0</td>
<td>260</td>
<td>112</td>
<td>578</td>
<td>146</td>
<td>130%</td>
</tr>
<tr>
<td>92-46</td>
<td>372</td>
<td>724</td>
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</tr>
</tbody>
</table>
Table 31. Sensitivity analysis for the nondominated treatments for the Adet-2 target group

<table>
<thead>
<tr>
<th>Variable N/P₂O₅ cost</th>
<th>Marginal N/P₂O₅ cost</th>
<th>Net benefit N/P₂O₅</th>
<th>Marginal net benefit N/P₂O₅</th>
<th>Marginal rate of return</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kg ha⁻¹)</td>
<td>(ETB ha⁻¹)</td>
<td>(ETB ha⁻¹)</td>
<td>(ETB ha⁻¹)</td>
<td></td>
</tr>
<tr>
<td>0-0</td>
<td>47</td>
<td>370</td>
<td>347</td>
<td></td>
</tr>
<tr>
<td>92-46</td>
<td>417</td>
<td>679</td>
<td>332</td>
<td>90%</td>
</tr>
</tbody>
</table>

Table 32. Summary of economic analyses of fertilizer trials for each zone and target group

<table>
<thead>
<tr>
<th>Zone</th>
<th>Check yield * (kg ha⁻¹)</th>
<th>Treatment with highest net benefit treatment</th>
<th>Yield of treatment in col.2 (kg ha⁻¹)</th>
<th>Yield increase (%)</th>
<th>Economic optimum treatment</th>
<th>Yield of treatment in col.5 (kg ha⁻¹)</th>
<th>Yield increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bekoji</td>
<td>1196</td>
<td>0-92</td>
<td>930</td>
<td>61</td>
<td>0-46</td>
<td>1699</td>
<td>42</td>
</tr>
<tr>
<td>Robe</td>
<td>1067</td>
<td>82-46</td>
<td>2104</td>
<td>97</td>
<td>41-0</td>
<td>1531</td>
<td>43</td>
</tr>
<tr>
<td>Sinana</td>
<td>993</td>
<td>0-46</td>
<td>1285</td>
<td>29</td>
<td>0-0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gondie</td>
<td>1807</td>
<td>82-23</td>
<td>2740</td>
<td>52</td>
<td>41-0</td>
<td>2334</td>
<td>29</td>
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<tr>
<td>Asasa</td>
<td>2698</td>
<td>20.5-92</td>
<td>3553</td>
<td>32</td>
<td>0-0</td>
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<td>-</td>
</tr>
<tr>
<td>Adet-1</td>
<td>1293</td>
<td>92-46</td>
<td>2409</td>
<td>86</td>
<td>92-46</td>
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<td>86</td>
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<tr>
<td>Adet-2</td>
<td>492</td>
<td>138-138</td>
<td>1991</td>
<td>305</td>
<td>92-46</td>
<td>1370</td>
<td>178</td>
</tr>
</tbody>
</table>

* adjusted yields used
† based on a nutrient price of ETB 1.38 kg⁻¹
Assuming a minimum acceptable rate of return of 100%

CALIBRATION OF FERTILIZER RESPONSE

Correlations among soil parameters measured at sowing time and grain yield response to fertilizer N and P₂O₅, following the methodology of Matar et al. (1987) revealed significant predictive relationships between N response and total soil N (p < 0.001), available soil P (p < 0.001), and organic matter (p < 0.05) (table 33) and between P₂O₅ response and available soil P (Mehlich method) (p < 0.001) and soil pH (p < 0.05) (table 34).

Predictive equations for N and P responses based on the data available from 33 trial sites distributed across the agro-ecological zones in this study follow:

\[
N_0/N_3 = 26.6 + 481.9 \log (\% N + 1) \\
r = 0.605, p < 0.001
\]

\[
N_0/N_3 = 21.8 + 78.8 \log (\% O.M.) \\
r = 0.450, p < 0.01
\]

\[
P_0/P_3 = -16.4 + 66.7 \log (P) \\
r = 0.552, p < 0.001
\]

\[
N_0/N_3 = -69.3 + 454.9 \log (\% N + 1) + 73.3 \log (P) \\
R^2 = 0.812, p < 0.001
\]

Considering that the latter equation accounts for 66% of the total variation in N response over the 33 trial sites, it could be used in the future to estimate response of bread wheat to N in highland agro-ecological zones not specifically included in this study. By contrast, the best predictive equation for P response, although highly significant, failed to account for sufficient variation (i.e. only 30%) to be useful in P₂O₅ response estimation.

Alternatively, the data were analyzed according to the procedure suggested by Cate and Nelson (1971) to determine critical levels of soil N and P associated with a high probability of response to the corresponding fertilizer nutrient. For soil N, the critical level thus determined was 0.213% N with an associated $r^2$ of 0.72. For available soil P (Mehlich), the critical level was 18.5 ppm with an associated $r^2$ of 0.30.

It may be necessary to determine whether the Mehlich method is the most suitable measure of...
### Table 33. Correlations among soil parameters related to fertilizer N response

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>O.M. (%)</th>
<th>N (%)</th>
<th>Log O.M. (%)</th>
<th>Log P (Mehlich)</th>
<th>Log (% N + 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O.M. (%)</td>
<td>-0.34*T</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(p = 0.052)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N (%)</td>
<td>-0.25</td>
<td>0.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ns</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Log % O.M.</td>
<td>-0.32</td>
<td>0.99</td>
<td>0.85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(p = 0.069)</td>
<td></td>
</tr>
<tr>
<td>Log P (Mehlich)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>***</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log (% N + 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>N response</td>
<td>0.26</td>
<td>0.43</td>
<td>0.60</td>
<td>0.45</td>
<td>0.58</td>
<td>0.61</td>
</tr>
<tr>
<td>(N0/N3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

O.M. = organic matter; *, **, *** indicate significance at the 5, 1 and 0.1% levels respectively; r values, n = 33; ns = not significant

### Table 34. Correlations among soil parameters related to fertilizer P response

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>O.M. (%)</th>
<th>N (%)</th>
<th>Log P (Mehlich)</th>
<th>Log % O.M.</th>
<th>Log P (Mehlich)</th>
<th>Log P (% N + 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O.M. (%)</td>
<td>-0.49†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N (%)</td>
<td>-0.46</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P (Mehlich)</td>
<td>0.43</td>
<td>-0.20</td>
<td>-0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ns</td>
<td>ns</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Log % O.M.</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>-0.46</td>
<td>0.99</td>
<td>0.89</td>
<td>-0.15</td>
<td>ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log P (Mehlich)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.49</td>
<td>-0.22</td>
<td>-0.21</td>
<td>0.98</td>
<td>-0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>**</td>
<td>ns</td>
<td>ns</td>
<td>***</td>
<td>ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log (% N + 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.45</td>
<td>0.91</td>
<td>1.00</td>
<td>-0.19</td>
<td>0.90</td>
<td>-0.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
<td>***</td>
<td>ns</td>
</tr>
<tr>
<td>P response</td>
<td>0.37</td>
<td>-0.09</td>
<td>-0.09</td>
<td>0.49</td>
<td>-0.08</td>
<td>0.55</td>
<td>-0.08</td>
</tr>
<tr>
<td>(P0/P3)</td>
<td></td>
<td>ns</td>
<td>ns</td>
<td></td>
<td>ns</td>
<td>***</td>
<td></td>
</tr>
</tbody>
</table>

O.M. = organic matter; *, **, *** indicate significance at the 5, 1 and 0.1% levels respectively; r values, n = 32; ns = not significant
Fertilizer recommendations for bread wheat

Figure 3. Relation between N (%) at sowing and yield response to N.

\[ Y = 26.6 + 481.9 \log(\%N + 1) \]
\[ r = 0.605 \quad (n=33) \]

Figure 4. Relation between O.M. (%) at sowing and yield response to N.

\[ Y = 21.8 + 78.8 \log(\%O.M.) \]
\[ r = 0.450 \quad (n=33) \]
soil P availability. In a greenhouse study of P response on Ethiopian soils, Olsen’s method gave the highest correlation with yield response to P (Tekalign and Haque 1991). Another field study on wheat indicated that the Bray II method was superior to Olsen’s (MOA 1989). In the current series of trials, P response was correlated to the log of Bray II values ($r = 0.74, p < 0.001$) and Mehlich values ($r = 0.69, p < 0.001$) at 18 sites, indicating that both were equally good at predicting P response. The correlation between the values from the two P analytical methods was also highly significant ($r = 0.83, p < 0.001$).

**FERTILIZER EFFECT ON SOIL PARAMETERS**

Analysis of the postharvest soil chemistry of individual plots at five trial sites revealed that certain soil parameters had been affected by fertilizer during the course of a single season (table 35). Total postharvest soil N was increased by fertilizer N at three of the five sites and by P$_2$O$_5$ at one site; the increases ranged from 0.035 to 0.77 percentage units. Postharvest available soil P (Mehlich) was increased by fertilizer P$_2$O$_5$ at four of the five sites, with the increases ranging from 7 ppm to 13 ppm. Soil pH decreased by 0.2-0.3 units with the application of urea fertilizer at three sites (i.e. 82 kg N ha$^{-1}$ at one site in Bekoji and 138 kg N ha$^{-1}$ at two sites in Adet). Soil organic matter increased with P$_2$O$_5$ fertilizer only at Bekoji, by 0.7 percentage units, and was not increased by N at any of the sites, despite the fact that above-ground biomass had responded significantly to fertilizer N and P$_2$O$_5$ at each of the five sites.

The soil parameter warranting major concern is pH, as increases in the other soil parameters such as soil N, available P, and organic matter represent improvements in soil fertility. Furthermore, it is important to note that the three sites registering a significant decrease in postharvest pH were located in the Adet and Bekoji zones, exhibiting the lowest mean preplant pH values (table 1). Soil pH is currently being monitored in long-term trials to study the effects of a range of fertilizer levels within different crop rotation systems, and in trials comparing alternate sources of inorganic N.
Table 35. Variation in postharvest measurements of soil parameters in response to fertilizer N and P2O5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>pH</th>
<th>Organic matter (%)</th>
<th>Total N (%)</th>
<th>Available P (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N effect:†</td>
<td>Bekoji</td>
<td>L** Q*</td>
<td>ns</td>
<td>L***</td>
</tr>
<tr>
<td></td>
<td>Gondie</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>Asasa</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>Adet-1</td>
<td>L* Q*</td>
<td>ns</td>
<td>L*** Q*</td>
</tr>
<tr>
<td></td>
<td>Adet-2</td>
<td>L*** Q*</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>P2O5 effect:†</td>
<td>Bekoji</td>
<td>L*</td>
<td>ns</td>
<td>L***</td>
</tr>
<tr>
<td></td>
<td>Gondie</td>
<td>ns</td>
<td>ns</td>
<td>L***</td>
</tr>
<tr>
<td></td>
<td>Asasa</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td></td>
<td>Adet-1</td>
<td>ns</td>
<td>L*</td>
<td>L**</td>
</tr>
<tr>
<td></td>
<td>Adet-2</td>
<td>ns</td>
<td>ns</td>
<td>L***</td>
</tr>
</tbody>
</table>

* • • « » • indicate significance at the 5, 1 and 0.1% levels respectively
† only main effects were significant: L = linear and Q = quadratic components; ns = not significant

FERTILIZER EFFECT ON WEEDS IN THE WHEAT CROP

Effect on wild oat panicle density

Data on wild oat panicle densities in the wheat crop at maturity were combined for analysis across five sites: one in Gondie, two in Bekoji, and two in Asasa. Mean wild oat panicle densities for the five trials ranged from 140 to 323 panicles m².

The combined analysis indicated that fertilizer N markedly increased the density of wild oat panicles (table 36); it has been suggested elsewhere that Avena fatua utilizes N more effectively than wheat, thereby enhancing its competitiveness with the crop under high N conditions (Carlson and Hill 1985). N at the rate of 100 kg N ha⁻¹ stimulated the emergence of grass weeds on bare soil in one study (Freyman et al. 1989), but in this study, wild oat panicle densities on wheat were increased significantly by as little as 20.5 kg N ha⁻¹. The quadratic nature of the response indicated that the maximum effect occurred at about 41 kg N ha⁻¹.

Conversely, the highest rate of fertilizer P2O5 significantly decreased wild oat panicle densities at four of the five sites, all of which exhibited greater yield response to P2O5 than to N. The effect of P2O5 was also significant in the combined analysis. The competitive reduction in wild oat panicle density was probably the result of increased early crop vigor (i.e. based on visual assessment) and the significant increase in crop biomass.

Wild oat panicle density was regressed on nutrient rates resulting in the following multiple regression equation:

\[
\text{Panicle density (no./m}^2\text{)} = 232.2 + 1.812 N (**) - 0.019 N^2 (***) - 2.491 P (***) + 0.001 N \times P^2 (*)
\]

\[R^2 = 0.86, p < 0.001\]

Density of wild oat panicle was negatively correlated with wheat grain yield \((r = -0.54, p < 0.05)\).
Table 37. Effect of fertilizer N and P₂O₅ levels on broadleaf weed seedling densities in wheat at 30 days postemergence

<table>
<thead>
<tr>
<th>Fertilizer (kg ha⁻¹)</th>
<th>Broadleaf weed density (seedlings/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gondie</td>
</tr>
<tr>
<td>0 N</td>
<td>238</td>
</tr>
<tr>
<td>6.8 N</td>
<td>263</td>
</tr>
<tr>
<td>13.7 N</td>
<td>244</td>
</tr>
<tr>
<td>27.3 N</td>
<td>254</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td></td>
</tr>
<tr>
<td>Significance (N)</td>
<td></td>
</tr>
<tr>
<td>0 P₂O₅</td>
<td>285a</td>
</tr>
<tr>
<td>23 P₂O₅</td>
<td>244ab</td>
</tr>
<tr>
<td>46 P₂O₅</td>
<td>236ab</td>
</tr>
<tr>
<td>92 P₂O₅</td>
<td>233b</td>
</tr>
<tr>
<td>LSD (0.10)</td>
<td>51</td>
</tr>
<tr>
<td>Significance (P₂O₅)</td>
<td>L</td>
</tr>
<tr>
<td>Mean</td>
<td>250</td>
</tr>
<tr>
<td>CV (%)</td>
<td>24.4</td>
</tr>
</tbody>
</table>

Values followed by different letters are significantly different.

† within experiments only N and P₂O₅ main effects were significant: L = linear, Q = quadratic components
* indicates significance at the 5% level

HI (r = -0.82, p < 0.001) and TKW (r = -0.58, p < 0.05) but was positively correlated with days to maturity (r = 0.70, p < 0.01). The negative correlations indicate that wild oat density and those specific parameters responded in opposite fashion to applied fertilizer (e.g. HI was increased by P₂O₅ and decreased by N). Wild oat panicle density was not significantly correlated with biomass, straw yield or plant height since these three parameters were increased by both N and P₂O₅, while wild oat density was increased by N and decreased by P₂O₅.

Effect on handweeding labor

The impact of fertilizer on early broadleaf weed growth was further reflected in the labor requirement for two handweedings (at 30 and 45 days post-sowing), measured at four sites in the Adet zone. Fertilizer N applied at the rate of 138 kg ha⁻¹ significantly increased handweeding labor relative to the check (table 38), attributable to an increase in broadleaf weeds since laborers are not able to reliably identify most grass weed species in a broadcast wheat crop. In a previous study, the density of five broadleaf weed species on wheat in the Gondie zone increased with the application of 36 kg N ha⁻¹ at sowing (Amanuel and Tanner 1991).

In the Adet zone, all of the N fertilizer was broadcast at sowing, which probably stimulated an early flush of weed growth. Split application of N, as practiced in the trials in the other zones, has been reported to be neutral in its effect on grain yield (Asnakew 1990). Split application of N should probably be recommended for smallholders, thereby minimizing weed competition and the requirement for handweeding and simultaneously reducing economic risk levels. The farmer would not apply the N topdressing until assured of good emergence and growing conditions.
Analysis of stripe rust data collected from three trials in the Gondie, Bekoji and Sinana zones revealed that N and P fertilizers significantly increased disease incidence in three and two zones, respectively (table 39). Disease increase caused by N was particularly pronounced in Bekoji and Sinana zones where stripe rust levels were high. The effect of P₂O₅ was less dramatic than that of N in each of these zones; in the Gondie zone it was not significant. N fertilizer was previously observed to increase the severity of both leaf rust (Puccinia recondita) and speckled leaf blotch (Septoria tritici) on wheat in Ethiopia (Amanuel and Tanner 1991), thought to be at least partially due to enhanced biomass production which altered the microenvironment for disease development.

Mean stripe rust infection levels on the semi-dwarf cultivar Dashen varied from 19.5% in Gondie to 65.8% in Bekoji. Dashen, a high-yielding bread wheat line released in 1984, exhibited trace amounts of stripe rust at specific locations in 1987. Subsequently, the cultivar’s downfall was swift; infection levels of up to 90% were recorded in 1988, particularly on the well-fertilized fields of the state farms in southern Ethiopia. Unfortunately, Dashen had been included in the fertilizer trial proposals prior to recognition of its high degree of susceptibility to stripe rust.

Correlations within each zone indicated that stripe rust infection level was positively associated with biomass, grain and straw yields in all zones and with plant height in the two zones for which data were available (table 40). Thus stripe rust increased in response to fertilizer N and P₂O₅ simultaneously with these other crop parameters, supporting the view that a modification of the microenvironment enhanced the disease.

Neither HL weight nor TKW were significantly correlated with stripe rust incidence at Gondie, where stripe rust levels were low. TKW was negatively correlated with stripe rust at Bekoji, where infection levels were high, indicating a probable reduction in grain yield below its potential.

### Table 39. Effect of N and P₂O₅ levels on stripe rust incidence

<table>
<thead>
<tr>
<th>Fertilizer (kg ha⁻¹)</th>
<th>Gondie</th>
<th>Bekoji</th>
<th>Sinana</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 N</td>
<td>15.3a</td>
<td>51.4c</td>
<td>44.0d</td>
</tr>
<tr>
<td>20.5 N</td>
<td>15.9b</td>
<td>59.3bc</td>
<td>47.4c</td>
</tr>
<tr>
<td>41 N</td>
<td>21.6ab</td>
<td>70.3a</td>
<td>53.6b</td>
</tr>
<tr>
<td>82 N</td>
<td>25.3a</td>
<td>82.2a</td>
<td>58.8a</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>6.6</td>
<td>11.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Significance (N)</td>
<td>L***</td>
<td>L***</td>
<td>L***</td>
</tr>
<tr>
<td>0 P₂O₅</td>
<td>17.2</td>
<td>51.0c</td>
<td>48.8b</td>
</tr>
<tr>
<td>23 P₂O₅</td>
<td>20.9</td>
<td>66.9b</td>
<td>50.7ab</td>
</tr>
<tr>
<td>46 P₂O₅</td>
<td>20.3</td>
<td>70.2a</td>
<td>51.1ab</td>
</tr>
<tr>
<td>92 P₂O₅</td>
<td>19.7</td>
<td>75.1a</td>
<td>53.2a</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>ns</td>
<td>11.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Significance (P₂O₅)</td>
<td>ns</td>
<td>L***</td>
<td>L**</td>
</tr>
<tr>
<td>Mean</td>
<td>19.5</td>
<td>65.8</td>
<td>50.9</td>
</tr>
<tr>
<td>CV (%)</td>
<td>47.8</td>
<td>36.2</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Values followed by different letters are significantly different. Within zones only N and P₂O₅ main effects were significant; L = linear and Q = quadratic components; ns = not significant; ***, *** indicate significance at the 1% and 0.1% levels respectively.

### Table 40. Correlations between stripe rust infection level and selected crop parameters

<table>
<thead>
<tr>
<th>Zone</th>
<th>Biomass</th>
<th>Harvest</th>
<th>Grain yield</th>
<th>Height</th>
<th>Straw yield</th>
<th>Days to heading</th>
<th>Days to maturity</th>
<th>Hectoliter weight</th>
<th>1000-kernel wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gondie</td>
<td>0.7161</td>
<td>0.148</td>
<td>0.732</td>
<td>0.737</td>
<td>0.684</td>
<td>0.622</td>
<td>0.353</td>
<td>-0.418</td>
<td>-0.090</td>
</tr>
<tr>
<td></td>
<td>** *</td>
<td>ns</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Bekoji</td>
<td>0.812</td>
<td>-0.018</td>
<td>0.476</td>
<td>0.9111</td>
<td>0.871</td>
<td>-0.612</td>
<td>-0.221</td>
<td>-</td>
<td>-0.556</td>
</tr>
<tr>
<td></td>
<td>***</td>
<td>ns (p&lt;0.1)</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>ns</td>
<td>*</td>
<td>ns</td>
</tr>
<tr>
<td>Sinana</td>
<td>0.822</td>
<td>0.300</td>
<td>0.801</td>
<td>-</td>
<td>0.802</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>***</td>
<td>ns</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>ns</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

*n = 16 (N by P₂O₅ interaction means) for each correlation

*, ***, *** indicate significance at the 5, 1 and 0.1% levels respectively; ns = not significant
The impact of stripe rust on the productivity of Dashen was assessed by comparing crop parameters at one site in Gondie and Bekoji zones, representing the lowest and the highest levels of stripe rust respectively (table 41). At Bekoji, grain yield increased to 2987 kg ha\(^{-1}\) with 92 kg P\(_{2}O_{5}\) ha\(^{-1}\), compared to 1530 for the check treatment (+95.2%). At Gondie, grain yield increased to 4276 kg ha\(^{-1}\) with 82 kg N and 23 kg P\(_{2}O_{5}\) ha\(^{-1}\), compared to 3271 for the control (+30.7%).

Although under normal circumstances, Bekoji has a longer, cooler growing season than Gondie (reflected in the relative heading periods of 102 and 83 days) and thus a higher wheat grain yield potential, stripe rust dramatically altered grain production at Bekoji in 1988. While biomass production was virtually equal at the two sites, grain yield, and as a result HI were reduced under the heavy stripe rust pressure at Bekoji. The reduction in grain yield could be attributed to both reduced seed set and decreased seed size, comparing the number of grains per square meter and TKW at Bekoji and Gondie.

The characteristics of N and P uptake were not apparently altered by stripe rust apart from its overriding influence on HI, reducing N harvest index (NHI) and phosphorus harvest index (PHI) accordingly at Bekoji. The percentage of grain N was similar at both sites as was the percentage of grain P. Grain N and P uptake were highly correlated (p < 0.001) with grain yield at both sites.

The constancy of grain N and P content was further apparent upon expressing nutrient use efficiency in terms of grain yield per unit grain nitrogen (NUE) or phosphorus (PUE), revealing consistent trends at both sites. At Gondie, NUE varied from 55 kg grain per kilogram of grain nitrogen at

### Table 41. Crop parameters for the stripe rust-susceptible cultivar Dashen grown in two contrasting environments in 1988

<table>
<thead>
<tr>
<th>Crop parameter</th>
<th>(mean value)</th>
<th>Gondie</th>
<th>Bekoji</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stripe rust (%)</td>
<td>20</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Days to heading</td>
<td>83</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>Biomass (kg ha(^{-1}))</td>
<td>10 349</td>
<td>10 577</td>
<td></td>
</tr>
<tr>
<td>Grass (kg ha(^{-1}))</td>
<td>3619</td>
<td>2344</td>
<td></td>
</tr>
<tr>
<td>Harvest index (%)</td>
<td>34.3</td>
<td>21.6</td>
<td></td>
</tr>
<tr>
<td>Grains/m(^2)</td>
<td>10 160</td>
<td>6947</td>
<td></td>
</tr>
<tr>
<td>TKW (g)</td>
<td>35.6</td>
<td>33.8</td>
<td></td>
</tr>
<tr>
<td>Grass N (kg ha(^{-1}))</td>
<td>73.3</td>
<td>47.6</td>
<td></td>
</tr>
<tr>
<td>NHI* (%)</td>
<td>66.7</td>
<td>40.1</td>
<td></td>
</tr>
<tr>
<td>Grass P (kg ha(^{-1}))</td>
<td>8.9</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>PHI* (%)</td>
<td>45.5</td>
<td>29.3</td>
<td></td>
</tr>
<tr>
<td>NUE(^{+})</td>
<td>50.5</td>
<td>49.5</td>
<td></td>
</tr>
<tr>
<td>PUE(^{+})</td>
<td>434.0</td>
<td>458.5</td>
<td></td>
</tr>
</tbody>
</table>

* NHI, PHI: nitrogen and phosphorus harvest index
* NUE, PUE: kg grain/kg nutrient uptake in grain

### Table 42. N and P uptake by the semidwarf wheat cultivar Dashen exposed to contrasting levels of stripe rust

<table>
<thead>
<tr>
<th>Fertilizer (kg ha(^{-1}))</th>
<th>Gondie (low stripe rust infection)</th>
<th>Bekoji (high stripe rust infection)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 N P(<em>{2}O</em>{5})</td>
<td>N uptake in grain (kg ha(^{-1})) NHIT (%) P uptake in grain (kg ha(^{-1})) P-HIT (%) HI (%)</td>
<td>N uptake in grain (kg ha(^{-1})) NHIT (%) P uptake in grain (kg ha(^{-1})) P-HIT (%) HI (%)</td>
</tr>
<tr>
<td>0 0</td>
<td>62.9 70.9 5.8 45.3 34.3</td>
<td>18.1 30.0 1.4 18.7 13.2</td>
</tr>
<tr>
<td>0 92</td>
<td>58.8 70.1 11.0 45.1 34.6</td>
<td>55.3 46.6 12.8 43.4 24.0</td>
</tr>
<tr>
<td>82 0</td>
<td>88.7 66.4 7.3 46.3 35.0</td>
<td>29.3 30.6 2.2 21.2 17.1</td>
</tr>
<tr>
<td>82 92</td>
<td>98.0 64.4 14.0 45.4 34.7</td>
<td>63.3 36.1 10.2 31.4 21.8</td>
</tr>
<tr>
<td>Mean</td>
<td>73.3 66.7 8.9 45.5 34.3</td>
<td>47.6 40.1 6.4 29.3 21.6</td>
</tr>
<tr>
<td>CV (%)</td>
<td>11.8 4.7 15.4 8.3 6.7</td>
<td>16.8 13.0 19.3 11.1 14.4</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>14.5 5.2 2.3 ns ns</td>
<td>13.3 8.7 2.1 5.4 5.2</td>
</tr>
<tr>
<td>Correlation with grain yield</td>
<td>0.984 0.468 0.716 0.162 0.317</td>
<td>0.987 0.637 0.892 0.841 0.853</td>
</tr>
</tbody>
</table>

* NHI, PHI: nitrogen and phosphorus harvest index respectively; ns = not significant
** *, *** indicate significance at the 1 and 0.1% levels respectively
0 N to 45 with 82 kg fertilizer N ha\(^{-1}\). At Bekoji, the corresponding values were 54 and 45 respectively. At Gondie, PUE ranged from 637 kg grain per kilogram of grain phosphorus at 0 P\(_2\)O\(_5\) to 289 with 92 kg fertilizer P\(_2\)O\(_5\) ha\(^{-1}\). At Bekoji, the corresponding values were 783 and 222.

For both sites, NHI decreased with higher levels of N fertilizer (table 42). Apparent recovery of fertilizer N in above-ground biomass ranged from 55% at 0 P\(_2\)O\(_5\) to 92% with 92 kg P\(_2\)O\(_5\) ha\(^{-1}\) at Gondie and from 43% at 0 P\(_2\)O\(_5\) to 71% with 92 kg P\(_2\)O\(_5\) ha\(^{-1}\) at Bekoji. Thus stripe rust infection may have reduced the overall efficiency of N uptake at Bekoji, but other agro-ecological factors could have also influenced N recovery.

PHI was increased significantly by 92 kg P\(_2\)O\(_5\) ha\(^{-1}\) at Bekoji but was not affected by either nutrient at Gondie. At Bekoji, mean PHI was reduced to 29% because of the negative effect of stripe rust on HI. Apparent recovery of fertilizer P in above-ground biomass was higher at Bekoji than at Gondie, averaging 52% and 38% respectively. This reflects the greater response to P\(_2\)O\(_5\) at Bekoji in terms of grain yield, grain P and straw P. At Gondie, the crop responded primarily to N.

CONCLUSIONS AND RECOMMENDATIONS

Although there is evidence in some of the industrialized nations that using fertilizer has reached excessive levels and may pose a threat to both human health and the environment, judicious and efficient use of fertilizer in Ethiopia has the potential to dramatically increase wheat yield, thereby increasing the national level of self-sufficiency for wheat grain, which has declined to under 70% during the 1980s.

Furthermore, the results presented in this report indicate two important factors:

- the zone-specific optimum fertilizer levels derived in this study vary markedly from the previous national blanket recommendation and from very recent attempts by MOA to refine fertilizer recommendations;
- compared to the common practice of nonapplication of fertilizer in wheat-based farming systems, the optimum nutrient levels generated for the zones included in this study resulted in mean grain yield increases ranging from 29% to 178%, sufficient to address the national wheat deficit. The associated total rates of return on farmers' investments exceeded 100%, using conservative estimates of the local market grain price and the yield adjustment required.

The nutrient rates recommended for the different zones and for farmers with differing levels of cash to invest could all be derived from urea and TSP. Thus only these two fertilizer compounds would be necessary for MOA's distribution system. Extension agents would play an important role in assisting peasant farmers to choose the appropriate fertilizer rate for their particular circumstances.

Analyses of the local fertilizer market from the supply point of view indicate that fertilizer unavailability is a critical constraint to realizing the potential benefits of zone-specific recommendations. Thus data from such studies of fertilizer response at the peasant farm level can provide policy makers with important information on which they base decisions to import fertilizers. It needs to be recognized that on-farm research staff with first-hand understanding of peasant farming systems and farmer conditions are in a unique position to identify policy constraints and to promote the necessary changes in the policy environment to complement and facilitate technological changes.

High rates of N, particularly when applied all at sowing, could exert a detrimental effect on wild oat density, the labor required for hand removal of broadleaf weeds, the incidence of stripe rust on susceptible cultivars, and soil pH. P can also increase stripe rust infection levels, presumably by increasing the crop's vegetative growth and altering the pathogen's microenvironment. However, by enhancing early crop vigor, P can increase the ability of wheat to competitively suppress wild oats. Both fertilizers increased postharvest residual soil fertility, potentially of benefit in future growing seasons and in the maintenance of soil organic matter.

Although demonstrating the potential benefits associated with zone-specific fertilizer recommendations for bread wheat in Ethiopia, this study indicates the need for caution with regard to the sustainability of increased fertilizer usage by peasant farmers. Long-term studies to monitor the effect of urea on soil pH have been initiated in Ethiopia as have studies of alternate N fertilizers. In the absence of other essential farm-level inputs, such as herbicides for weed control and improved seed of cultivars resistant to stripe rust, the benefits associated with fertilizer usage could be markedly reduced.
REFERENCES


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Byerlee, D. 1980. CIMMYT economics training note. CIMMYT, Mexico, D.F.


## APPENDIXES

Appendix A. Results of individual analyses of variance for grain yield for each of the 52 sites in the N x P factorial fertilizer trials

<table>
<thead>
<tr>
<th>Zone-year/site</th>
<th>Significance</th>
<th>Mean grain yield (kg ha⁻¹)</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>P</td>
<td>N x P</td>
<td></td>
</tr>
<tr>
<td><strong>Bek88/Fikre Mekuria</strong></td>
<td>ns</td>
<td>***</td>
<td>ns</td>
</tr>
<tr>
<td><strong>Bek88/Shene Offga</strong></td>
<td>*</td>
<td>***</td>
<td>ns</td>
</tr>
<tr>
<td><strong>Bek88/Teka Belayneh</strong></td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td><strong>Bek88/Kasim Feto</strong></td>
<td>ns</td>
<td>***</td>
<td>ns</td>
</tr>
<tr>
<td><strong>Bek89/Tädele G.Tsadik</strong></td>
<td>ns</td>
<td>***</td>
<td>*</td>
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<tr>
<td><strong>Bek89/Adugna Debele</strong></td>
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<td>***</td>
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<td>*</td>
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<tr>
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### Appendix A. contd.

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<tr>
<th>Zone-year/site†</th>
<th>Significance</th>
<th>Mean grain yield (kg ha⁻¹)</th>
<th>CV (%)</th>
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† Bek = Bekoji, Gon = Gondie, As = Asasa, Ro = Robe, Sin = Sinana, Ad = Adet
* *, **, *** indicate significance at the 5, 1 and 0.1 levels respectively; ns = not significant

### Appendix B. Results of combined analyses of variance for biomass with sites grouped within each recommendation domain

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<td>Mean (kg ha⁻¹)</td>
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<td>5 560</td>
<td>11 005</td>
<td>6 101</td>
<td>12 176</td>
<td>10 020</td>
<td>6 640</td>
<td>4 076</td>
<td>3 430</td>
<td>4 472</td>
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<tr>
<td>CV (%)</td>
<td>14.6</td>
<td>20.9</td>
<td>10.1</td>
<td>16.5</td>
<td>11.0</td>
<td>19.5</td>
<td>21.3</td>
<td>34.1</td>
<td>27.5</td>
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1989B refers to the B season
* *, **, *** indicate significance at the 5, 1 and 0.1 levels respectively; ns = not significant
### Appendix C. Results of combined analyses of variance for straw yield with sites grouped within each recommendation domain

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<tbody>
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<tr>
<td>Nitrogen (N)</td>
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<td>***</td>
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<td>Phosphorus (P)</td>
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*, **, *** indicate significance at the 5, 1 and 0.1 levels respectively; ns = not significant

### Appendix D. Results of combined analyses of variance for harvest index with sites grouped within each recommendation domain

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*, **, *** indicate significance at the 5, 1 and 0.1 levels respectively; ns = not significant
### Appendix E. Results of combined analyses of variance for plant height with sites grouped within each recommendation domain

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<td>ns</td>
<td>***</td>
<td>ns</td>
<td>***</td>
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<td>Phosphorus (P)</td>
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1989B refers to the B season

*, **, *** indicate significance at the 5, 1 and 0.1 levels respectively; ns = not significant

### Appendix F. Results of combined analyses of variance for days to heading with sites grouped within each recommendation domain

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*, **, *** indicate significance at the 5, 1 and 0.1 levels respectively; ns = not significant
### Appendix G. Results of combined analyses of variance for days to maturity with sites grouped within each recommendation domain

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*, **, *** indicate significance at the 5, 1 and 0.1 levels respectively; ns = not significant

### Appendix H. Results of combined analyses of variance for hectoliter weight with sites grouped within each recommendation domain

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*, **, *** indicate significance at the 5, 1 and 0.1 levels respectively; ns = not significant
Appendix I. Results of combined analyses of variance for 1000 kernel weight with sites grouped within each recommendation domain

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Sinana 1989B refers to the B season
*, **, *** indicate significance at the 5, 1 and 0.1 levels respectively; ns = not significant