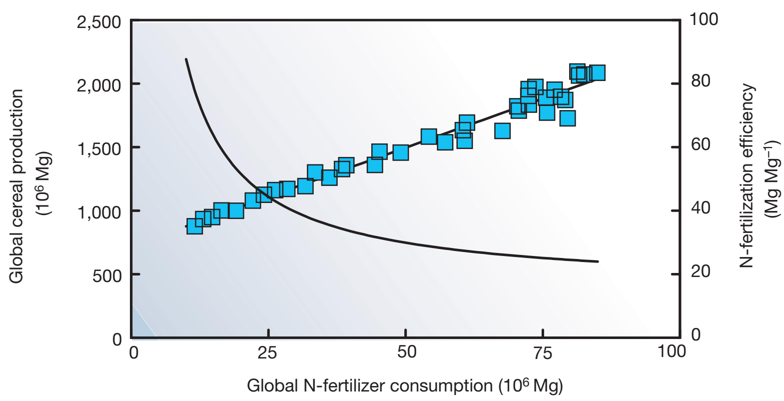

Figure 1 Regression between global cereal production and nitrogen-fertilizer consumption, showing a relatively constant increase in production per unit increase in fertilizer use, and no evidence of diminishing returns. Boxed points are actual data (from the United Nations Food and Agriculture Organization 2002; http://apps.fao.org); the thin line ($P = 15.47f + 722.3$) is the result of a regression of production on fertilizer consumption. Even within this linear relationship, nitrogen-fertilization efficiency (calculated by dividing the regression line by fertilizer consumption; thick line) declines as fertilizer consumption increases.

ishing returns from fertilization (Fig. 1; data from the United Nations Food and Agriculture Organization). The term 'diminishing returns', which was first used in relation to agricultural productivity[2,3], describes a decline in the marginal output, or the increase in output per unit change in input, when the level of a variable input is increased[4], rather than a decline in the ratio of output to input. 'Nitrogen-fertilization efficiency', as calculated by Tilman *et al.*[1], is not a useful way to represent the effectiveness of fertilization.

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Tilman et al. *reply* — An important question that arises from Hafner's comment is why global crop production[1] should appear to be a linear function of global nitrogen fertilization, even though crop production has consistently shown diminishing returns from increased fertilization in field trials[2–4]. Although we concur that our Fig. 2b does not unambiguously demonstrate diminishing returns, evidence based on data from the United Nations Food and Agriculture Organization indicate that global crop production and yield[5] do indeed show diminishing returns for increased fertilization.

Crop responses to nitrogen fertilizer are expected to exhibit diminishing returns because yields may be limited simultaneously by the availability of light, water, nitrogen and the other essential nutrients. As nitrogen fertilizer is added to alleviate nitrogen deficiency, other resources will then become limiting, causing the crop's response to nitrogen to diminish[6]. Moreover, nitrogen losses increase with increased nitrogen application because surplus inorganic nitrogen (NO_3^- and NH_4^+) in the root zone is leached into the groundwater or lost to the atmosphere in gaseous form.

Hafner's univariate analysis ignores other agricultural inputs, particularly irrigation, that change simultaneously with increasing nitrogen fertilization. It is more appropriate to determine the dependence of global crop production (cereals, coarse grains and root crops) and global crop yield (production divided by global land dedicated to these crops) on global nitrogen fertilization while controlling for global irrigation.

In tests for a nonlinear (saturating) effect of nitrogen fertilization (J. Fargione *et al.*, unpublished results), one using global rates of production, fertilization and irrigation per hectare, and the other using production, fertilization and irrigation per hectare, we found a significantly saturating effect of nitrogen fertilization. Multiple regression of yearly global crop production on irrigation and nitrogen fertilization revealed a significant positive linear effect of irrigation ($F_{1,36} = 56.9$, $P < 0.0001$) and a simultaneous saturating (quadratic) effect of nitrogen fertilization. The nitrogen effect had a significantly positive linear ($F_{1,36} = 13.8$, $P = 0.0007$) and a significantly negative quadratic ($F_{1,36} = 7.23$, $P < 0.018$) term for 1961–2000. The negative quadratic term in the fitted model gave a curve for the dependence of global crop production on nitrogen fertilization that approached its peak at current global rates of nitrogen fertilization.

A multiple regression of global crop yield (production per hectare) on global irrigation per hectare and on global nitrogen fertilization per hectare also indicated diminishing returns (J. Fargione *et al.*, unpublished results). Global crop yield increased with irrigation per hectare ($F_{1,36} = 64.2$, $P < 0.0001$) but was a saturating function of fertilization per hectare, with a positive linear term ($F_{1,36} = 13.4$, $P = 0.0008$) and a negative quadratic term ($F_{1,36} = 4.36$, $P = 0.044$) for this 40-year period. The fitted curve for yield approached its peak at current global rates of nitrogen fertilization. Twenty-two similar analyses for each of 11 periods from 1961 through to each year from 1990 to 2000 also revealed significantly diminishing returns.

Although multiple regressions that use collinear variables cannot demonstrate causal relationships unambiguously, and although we did not control for improved crop varieties, it is likely that there have been diminishing returns of increased global nitrogen fertilization at least since 1990. If this is the case, other technologies (see ref. 7, for example) may help to increase global crop yields; indeed, the United States' maize yield increased by almost 40% from 1980–2000 without any increase in nitrogen fertilization[6]. Plant breeding, biotechnology and advances in crop and soil management will probably account for most of the future increases in global crop production, without the negative environmental effects that are attributed to nitrogen fertilizers.

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