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Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production

ANDREW BALMFORD*†, RHYS. E. GREEN*‡ and JÖRN P. W. SCHARLEMANN*‡§

**Conservation Biology Group, Department of Zoology, University of Cambridge, Downing St, Cambridge CB2 3EJ, UK, †Percy FitzPatrick Institute of African Ornithology, Department of Zoology, University of Cape Town, Private Bag, Rondebosch 7701, South Africa, ‡Royal Society for the Protection of Birds, The Lodge, Sandy, Bedfordshire SG19 2DL, UK, §Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK*

Abstract

How can rapidly growing food demands be met with least adverse impact on nature? Two very different sorts of suggestions predominate in the literature: wildlife-friendly farming, whereby on-farm practices are made as benign to wildlife as possible (at the potential cost of decreasing yields); and land-sparing, in which farm yields are increased and pressure to convert land for agriculture thereby reduced (at the potential cost of decreasing wildlife populations on farmland). This paper is about one important aspect of the land-sparing idea – the sensitivity of future requirements for cropland to plausible variation in yield increases, relative to other variables. Focusing on the 23 most energetically important food crops, we use data from the Food and Agriculture Organisation (FAO) and the United Nations Population Division (UNPD) to project plausible values for 2050 for population size, diet, yield, and trade, and then look at their effect on the area needed to meet demand for the 23 crops, for the developing and developed worlds in turn. Our calculations suggest that across developing countries, the area under those crops will need to increase very considerably by 2050 (by 23% under intermediate projections), and that plausible variation in average yield has as much bearing on the extent of that expansion as does variation in population size or per capita consumption; future cropland area varies far less under foreseeable variation in the net import of food from the rest of the world. By contrast, cropland area in developed countries is likely to decrease slightly by 2050 (by 4% under intermediate projections for those 23 crops), and will be less sensitive to variation in population growth, diet, yield, or trade. Other contentious aspects of the land-sparing idea require further scrutiny, but these results confirm its potential significance and suggest that conservationists should be as concerned about future agricultural yields as they are about population growth and rising per capita consumption.

Keywords: agriculture, agricultural yield, conservation, cropland, crop production, diet, farming, human population, land sparing, trade

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Introduction

How can an expanding human population feed itself better without losing most of what still remains of wild nature? This is one of the greatest challenges facing conservation scientists this century. Cropland or permanent pasture already covers more than half of all agriculturally useable land, while temporary grazing or degraded farmland accounts for a substantial (though unquantified) fraction of the remainder (Richards, 1990; Young, 1999; FAO, 2001). The pressure from farming is increasing: while the extent of cropland and pasture has recently shrunk in developed countries (by ~ 1.3% 1961–1999; FAO, 2001), this has been more than offset by continued expansion in developing countries

Correspondence: Andrew Balmford,
e-mail: a.balmford@zoo.cam.ac.uk

($\sim$ 18.8% increase in 1961–1999). Moreover, while food crop yield per unit area doubled over the past 40 years, this required enormous increases in inputs to farmed land (such as irrigation, fossil fuel energy, pesticides, and fertilizers), in the developing and developed world alike (FAO, 2001; Tilman *et al*., 2001, 2002).

As a consequence, agriculture threatens more species than any other human activity, especially in developing countries. For example, analyses of threats to birds (the only taxon for which sufficient information exists) show that the conversion of natural habitats to cropland and pasture and the intensification of their use together account for 37% of threats to globally threatened species (BirdLife International, 2000; Green *et al*., 2005). This figure is substantially higher in developing countries (40% of threats to 1039 threatened species) than in developed countries (24% of threats to 225 threatened species). Moreover, the relative importance of agriculture as a source of threat looks set to increase. An examination of near-threatened bird species (which are expected to become threatened in the near future – IUCN Species Survival Commission, 2001) shows that farming accounts for 57% of threats to near-threatened species in developing countries (687 species), and 33% of threats to developed-country species (95 species; BirdLife International, 2000; Green *et al*., 2005). With over 800 million people going to bed hungry (Sanchez & Swaminathan, 2005), with our current population of $\sim$ 6.4 billion forecast to increase to $\sim$ 7.4–10.6 billion by 2050 (United Nations Population Division, 2003), and with overall food demand expected to rise two- to threefold over the same interval (Bongaarts, 1996; Ruttan, 2002; Tilman *et al*., 2002), how should conservationists respond?

Broadly speaking, two kinds of solutions have been proposed (for a theoretical discussion of their likely relative merits, see Green *et al*., 2005). One approach, which can be labelled wildlife-friendly farming, involves reductions of inputs of pesticides and fertilizers and their effects on nontarget organisms, and the retention of patches of nonfarmed habitats as well as extensively farmed seminatural habitats within the farmed landscape (Pain & Pienkowski, 1997; Daily, 2001; Rosenzweig, 2003a, b). Such wildlife-friendly farming is strongly advocated by conservationists in Europe, where the European Union (EU) pays its farmers a total of $\sim \$2.7\,\text{billion yr}^{-1}$ to adopt environmentally sensitive agricultural practices (European Environment Agency, 2002). There is also growing evidence from a range of developing countries that around a half of the species found in an area's unconverted habitats are usually still present under low-intensity farming (Janzen, 1973; Roth *et al*., 1994; Estrada *et al*., 1997, 1998; Greenberg *et al*., 1997; Pagiola *et al*., 1997; Medellín *et al*., 2000; Ricketts *et al*., 2001; Vosti *et al*., 2001; Goehring *et al*., 2002; Hughes *et al*., 2002; Daily *et al*., 2003; Donald, 2004; Naidoo, 2004; Scholes & Biggs, 2005). This has been used to argue for the widespread adoption of wildlife-friendly farming in the developing world too (e.g. Daily, 2001; Rosenzweig, 2003a, b). Obviously, techniques that enhance wildlife populations on farmed land without any negative effects on yield should be encouraged unequivocally (McNeely & Scherr, 2001; Pretty, 2002; Rosenzweig, 2003a, b). However, because much wildlife-friendly farming in practice reduces agricultural yields (as evidenced, for example, by the need for the EU to make agrienvironment payments to its farmers), it generally requires more land to be farmed to meet any given production target than does conventional agriculture. This point underlies a second, very different approach to reconciling food production and conservation goals – the idea of sparing land from conversion to agriculture (or for restoration for wildlife) by maximizing yields on already-converted land.

The notion of land-sparing is rarely discussed by conservation scientists (for exceptions, see Robinson, 1994; Tilman *et al*., 2002; Potts, 2003; Donald, 2004; Scholes & Biggs, 2004; Mooney *et al*., 2005), but is widely advocated in the development and agriculture literature (Goklany *et al*., 1992; Southgate, 1994; Waggoner, 1995; Ausubel, 1996, 2000; Avery, 1997; Barbier & Burgess, 1997; Cassman, 1999; Angelsen & Kaimowitz, 2001; Lee & Barrett, 2001; Waggoner & Ausubel, 2001; Borlaug, 2002). Evidence of the scale of past land-sparing comes from retrospective calculations showing that without the yield increases which they achieved over the past 40 years, India would require twice and China and USA three times today's area of cropland in order to meet current demands (Borlaug, 2002; see also Goklany & Sprague, 1992; Waggoner, 1995; Waggoner *et al*., 1996; Goklany, 1998). Prospective estimates of the potential for land-sparing under continued yield growth appear equally impressive. Paul Waggoner (1995), for instance, has calculated that increasing mean global yields by a factor of 2.5 by 2050 would enable a slight increase in per capita food production, for a population of 10 billion, while reducing cropland area by 25% (see also Ausubel, 1996; Goklany, 1998; Waggoner & Ausubel, 2001). These estimates have been criticised for being unduly optimistic about the prospects for sustained growth in crop yields (e.g. Ruttan, 1999, 2002); they also do not explicitly address the major differences in population growth, agricultural expansion, and the resulting threats to biodiversity, between developing and developed countries. Therefore, we considered it timely to extend these calculations to take into account recent estimates of likely changes in population size, diet, and yield, and in particular, to examine separately the scope for land-sparing in more and less developed regions of the world.

This paper examines the likely relative impact on the area of cropland needed by 2050 of a plausible range of future population sizes, per capita levels of crop production, and crop yields. We assess potential changes in the developing and developed worlds separately, but also take into account trade between the two, and specifically look into how much land-sparing might realistically be achieved in biodiversity-rich developing countries by increased food imports to them from developed countries (Goklany, 1998). While, wherever possible, we have based our projections on statistical analyses of the best available data, readers should bear in mind that extrapolating any recent time series 50 years into the future brings with it substantial uncertainty. Specific estimates of any of our variables are thus unreliable. Nevertheless, we believe our results do shed light on the likely relative leverage of different variables on the future area needed for food production, and as such have some potentially useful implications for agricultural and conservation policy.

Data and methods

Data sources

We used two main data sources. For information on recent population size and projections for 2050, we used *World Population Prospects: the 2002 Revision* (United Nations Population Division, 2003). For information on trends over the past 40 years in population size, cropland area, crop production, crop yield per unit area, and import and export of crop products, we used *FAOSTAT* (FAO, 2001). Detailed interpretation of the FAO crop data is hampered by inconsistencies across countries and years in reporting dates, and in methods of estimating yields, outputs, and area under farming. Nevertheless, these data are the only global information available.

UNPD and FAO differ slightly in their classification of 'more' and 'less developed' countries. For consistency we recalculated the UNPD population totals for more and less developed countries using the FAO definition (treating all nations that were formerly part of the USSR, as well as Israel and South Africa, as more developed, and Greenland, Bermuda and St Pierre et Miquelon as less developed); we labelled these groups 'developed' and 'developing', respectively.

Cropland area, crop production, and yield

We used data on crop production (harvested mass in tonnes) and the area (ha) grown of specific crops in each country from FAO (2001). We focused on energy-providing crops (rather than luxury or nonfood crops) because we could make projections of future requirements for these by converting crop mass statistics to their energetic equivalents (kilocalories, kcal), using data provided by Chatfield (1953), Duke (1983) and Souci *et al*. (2000). Specifically, we calculated total production (in energetic terms) of the 23 energetically most important food crops: paddy rice, maize, wheat, sugar beet, sugar cane, oil palm fruit, soy beans, barley, potatoes, cassava, sorghum, sweet potatoes, groundnuts, millet, onions, oats, coconuts, sunflower seeds, fresh vegetables, bananas, plantains, grapes, and yams. These crops include all the world's staples, currently account for 72% and 44% of the developing and developed world's cropland area, respectively, and represent 60% of total tonnage harvested in 2000. We then calculated yield for all developing and developed countries by dividing total production at harvest of our 23 focal crops by the sum of the area of these crops grown in those countries in that year.

Trade

We wished to estimate the annual net imports (imports minus exports), in terms of energy, of the aggregate of the 23 energetically most important crops between the developing and developed worlds. We used data on trade in raw and derived crop products from FAO (2001). Of all the variables we considered, we found trade the hardest to quantify, because of a combination of apparent errors in reported data and the fact that besides raw crops, trade statistics deal with derived crop products, not all of which could be easily converted into kcal equivalents. About 80% of the traded tonnage of the 23 energetically important crops was in raw products (in which case we used the same conversion factors as above) or in derived products whose tonnage we were able to convert into its kcal equivalent (although this conversion ignored product losses between harvest and trade). We treated the remaining 20% of the traded tonnage, which was of products for which we could not devise conversion factors, as if it was in tonnes of raw product. The inaccuracies introduced by doing this will vary in magnitude and direction among crops and products – for instance, derived products in which water has been added will have a lower energy content per tonne than the raw product, while those that have been dried will have a higher energy content. These errors will tend to balance out to some extent, and should be less than the error that would arise from excluding this 20% of traded tonnage from the analysis.

We next calculated the difference between the sums of imports to all developing countries and of exports from these countries (in kcal yr^{-1}) for each year from

1961 to 1999. These data include imports and exports from one developing country to another, but these cancel out in the calculation to leave the net trade between the developed and developing worlds. We then expressed these net imports as a percentage of the total energetic value of the annual harvest of the 23 crops in the developing world.

Per capita crop harvest adjusted for trade

We defined per capita crop harvest (PCCH) as the energy value of the annual harvest of the 23 most important food crops, divided by population size, and by 365 (to give a daily rate, for comparison with recommended daily allowances). PCCH is an appropriate metric for estimating the impact of diet on cropland area, but note that it differs from dietary intake because of post-harvesting losses, because it does not cover all food crops, and because some of the production of our 23 crops is consumed by livestock. We wished the energy from food crops to be attributed to the part of the world in which it is consumed, so we adjusted PCCH values for trade by adding the energy value of the net imports to developing countries to the numerator for developing-world PCCH, and conversely subtracting it from the numerator for developed countries.

Projection of future yield

In order to project future requirements for cropland, we needed first to make a range of projections of yield,

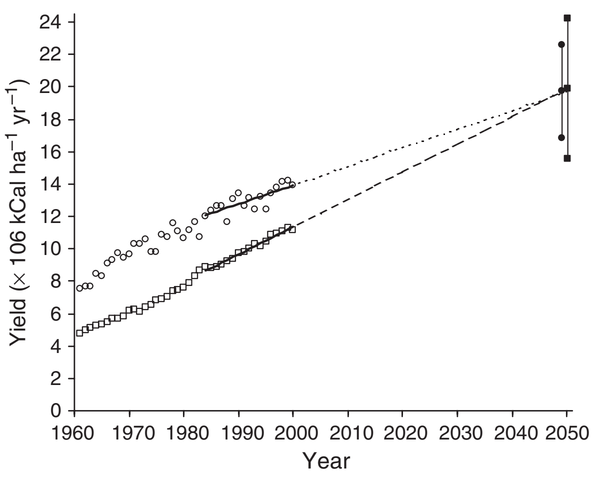

Fig. 1 Recent (1961–2000) and projected future energy yields of 23 crops in developed (○) and developing countries (□). Continuous lines represent least-squares linear regression fits to data from 1984 to 2000, while dashed lines show projections to 2050 for developed (······) and developing (- - - -) countries. Low, intermediate and high projected yields for 2050 for developed and developing countries are shown as filled circles and squares, respectively.

trade, PCCH and population. We used empirical data on recent trends to guide our projections for crop yields in 2050. For both the developing and the developed worlds, we plotted the annual mean energy yield of the 23 crops (expressed in kcal ha^{-1} yr^{-1}) against year for the period 1961–2000 (Fig. 1). Visual inspection suggested a possible change in trends after 1983, so we used linear regression models for the period 1984–2000 for projection. Note however that our findings are little changed if our regressions use all data back to 1961. For developing countries, the regression model was:

$$\text{Yield}(\text{kcal ha}^{-1}\,\text{yr}^{-1}) = (170\,468 \times \text{years since 1983}) + 8\,468\,299$$

and gave a good fit to the data ($r^2 = 0.98$, $F_{1,15} = 698.30$, $P < 0.001$, $N = 17$). For developed countries, the fit of the linear regression model was less good:

$$\text{Yield}(\text{kcal ha}^{-1}\,\text{yr}^{-1}) = (115\,614 \times \text{years since 1983}) + 11\,961\,747$$

($r^2 = 0.62$, $F_{1,15} = 24.84$, $P < 0.001$, $N = 17$). These results imply that in absolute and relative terms, the rate of yield growth is now considerably higher in developing countries.

For our intermediate, high and low projections, we then assumed the observed linear growth would continue at present rates, would be 50% higher, or would be 50% lower, through to 2050. These projections gave estimated yields in 2050 of 19.89, 24.25 and 15.53×10^6 kcal ha^{-1} yr^{-1} respectively, for developing countries (compared with 11.37×10^6 kcal ha^{-1} yr^{-1} in 2000), and 19.71, 22.59 and 16.82×10^6 kcal ha^{-1} yr^{-1}, respectively for developed countries (compared with 13.93×10^6 kcal ha^{-1} yr^{-1} in 2000; see Fig. 1). For comparison, we also examined what might happen to cropland area if there was zero growth and yield stagnated at year 2000 values.

We assessed the plausibility of our projections by comparison with the literature. Most published yield forecasts express growth in percentage terms (even though most authors agree growth is now becoming less than exponential – e.g. Bongaarts, 1996; Evans, 1997; Alexandratos, 1999; Conway & Toenniessen, 1999; Ruttan, 1999; Cassman *et al*., 2003; Rosegrant & Cline, 2003). Expressed in these terms, for developing countries the linear growth in our intermediate projection corresponds to 1.50% yr^{-1} in 2001, dropping to 0.86% yr^{-1} in 2050, or an overall mean of 1.13% yr^{-1}. Overall mean values for our high and low projections for developing countries are 1.53% yr^{-1} and 0.63% yr^{-1}. These values are less optimistic than some published estimates (Waggoner, 1995; Ausubel, 1996; Goklany, 1998; Waggoner & Ausubel, 2001), which suggest global mean growth of 1.5% yr^{-1} or more (and by implication, higher growth still in the developing world). On the other hand, they correspond quite closely to most recent forecasts for the developing world, which range from 0.66% yr^{-1} to 1.76% yr^{-1} (e.g. Alexandratos, 1999; Cassman, 1999; Döös & Shaw, 1999; Rosegrant *et al.*, 2001a, b). Likewise, our projections for developed countries (intermediate: 0.83% yr^{-1} in 2000 dropping to 0.59% yr^{-1} in 2050, or 0.70% yr^{-1} overall; high: 0.97% yr^{-1} overall; low: 0.38% yr^{-1} overall) correspond roughly to the range of values forecast in the literature. Therefore, we consider our three main projections to be plausible, but suggest that the fourth – of zero yield growth to 2050 – is unjustifiably pessimistic.

Projection of future trade

Recently, the developing world has been a net importer of the 23 crops, in terms of energy (Fig. 2). The recent accountable annual net trade was $\sim$5% of total developing-world production (mean 1984–1999 = 4.7%, $N = 16$ years). This figure lies within the range of previously published estimates of 3% for all crops (Bongaarts, 1996), and 9% (Conway, 2001) and 15% (Goklany, 1998) for cereals. Net trade has increased markedly since the 1960s and may still be rising (even as a proportion of developing-world production – Fig. 2). On the other hand, from the perspective of developing country farmers and governments, very substantial future increases in net imports of staple foods have been argued to be highly undesirable economically (Conway & Toenniessen, 1999, Evans, 2003; though for a different view, see Goklany, 1998) For our 2050 projections we thus suggest that net import values of 5%, 10%, and 15% of developing-world harvest constitute feasible low, intermediate and high projections (see also Conway, 2001).

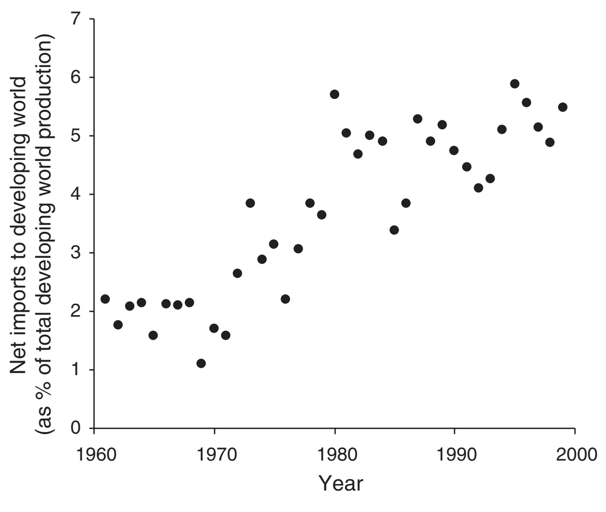

Fig. 2 Recent (1961–1999) trend in net imports to the developing world. Net trade is expressed as the difference between imports and exports (expressed in kcal yr^{-1}) of 21 of our 23 crops (two are not traded in their raw form according to FAO, 2001) and 78 products derived from them, as a percentage of total production of the 23 crops (in kcal yr^{-1}) in the developing world.

Projection of future PCCH

Our simplest projection to 2050 of the per capita requirement for energy from food crops is to assume that it will remain the same as our most recent estimates of trade-adjusted PCCH. These are 4100 kcal $person^{-1}\,d^{-1}$ for the developing world and 7833 kcal $person^{-1}\,d^{-1}$ for developed countries in 2000. We adopt the latter figure as our only projection for developed countries, but take the value for the developing world as our lowest projection of three. If conditions for people in the developing world were to improve markedly then a high projection for PCCH in the developing world in 2050 is the adjusted PCCH in the developed world in 2000. Perhaps more likely is the average of these two extremes (5966 kcal $person^{-1}\,d^{-1}$), which we use as our intermediate projection. Are these projections likely to be realistic?

To assess this, we examined recent temporal trends in trade-adjusted PCCH, calculated as described above. Plots of PCCH against year for the period 1961–1999 suggested a possible change in temporal trend in $\sim$1983 (Fig. 3), so we restricted regression analyses to the period 1984–2000. This indicated a strong and steady increase in adjusted PCCH for the developing world over time, which continued during the period 1984–2000. The fitted regression model for this period is:

$$\text{Trade-adjusted PCCH}(\text{kcal person}^{-1}\,\text{d}^{-1}) = (31.6 \times \text{years since 1983}) + 3552.2$$

($r^2 = 0.87$, $F_{1,15} = 97.12$, $P < 0.001$, $N = 17$ years). Extrapolating this regression line to 2050 gives a developing-world PCCH of 5817 kcal $person^{-1}\,d^{-1}$. This is very close to our intermediate projection. Our low projection corresponds to Döös & Shaw's (1999) Level 1 diets, where per capita demand remains unchanged. Our high projection (which also corresponds to developed-world PCCH in the late 1960s) is perhaps unlikely but might occur if recent rapid increases in the production and consumption of grain-fed meat in developing countries continue (FAO, 2001; Myers & Kent, 2003; Green *et al.*, 2005). We take this examination of recent trends to indicate that our three developing-world PCCH projections are likely to span the range of plausible outcomes and that the intermediate projection is particularly plausible. For the developed world, the temporal pattern in PCCH is weaker and has changed from being

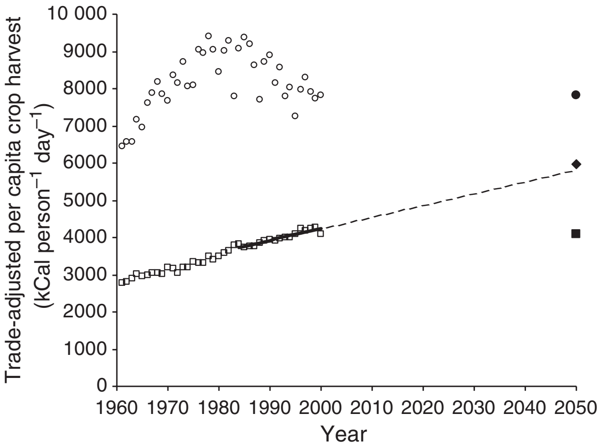

Fig. 3 Recent (1961–2000) and projected future values of per capita crop harvest for a combination of 23 major food crops (see text) in developed (○) and developing countries (□). The continuous line represents a least-squares linear regression fitted to developing countries from 1984 to 2000, while the dashed line shows its projection to 2050. All observed values and lines are for per capita crop harvest (PCCH) adjusted for trade. The three symbols on the right show (from the bottom) our low, intermediate and high projections for developing-country trade-adjusted PCCH in 2050; the upper symbol also shows our projected trade-adjusted PCCH value for the developed world. The lower and upper symbols correspond to year 2000 PCCH values for the developing and developed world, respectively, and the middle symbol to their mean.

positive to negative since 1983 (Fig. 3), presumably because of a combination of a reduction in waste, an increase in the efficiency with which crops are converted into meat, and a decrease in per capita meat consumption (FAO, 2001). Extrapolating the post-1983 trend would yield a highly implausible developed-world PCCH (lower than that for the developing world). In view of this complex pattern we do not think that any statistical model fitted to the data could be extrapolated to yield a plausible projected value. Our projection that instead developed-world PCCH will remain unchanged corresponds to Döös & Shaw's (1999) assumptions.

Projection of future population

We used the low, medium, and high variants of the UNPD projection to 2050 (United Nations Population Division, 2003) as our low, intermediate, and high projected population sizes. These suggest that the total population of the developing world will rise from ~ 4.7 billion in 2000 to 6.2, 7.5, or 9.1 billion in 2050, respectively, and for the developed world will change from ~ 1.3 billion in 2000 to 1.2, 1.4, or 1.5 billion. Note that these figures are based on UNPD projections for developed and developing countries as defined by FAO, not UNPD (see *Data sources* above). The main difference between the three UNPD variants is the rate at which fertility declines in less developed countries (United Nations Population Division, 2003). For comparison, we also examined what might happen if fertility remained constant through to 2050 (resulting in estimated developing- and developed-world populations of 11.4 and 1.3 billion); however, this trajectory is considered extremely unlikely (Lutz *et al*., 2001), and so here we do not present detailed analyses of its likely consequences.

Projection of future cropland area

We estimated the area of the developing (developed) world needed to grow the 23 energetically most important food crops in 2050 by first calculating the total production of these crops required by the population of the developing (developed) world as projected trade-adjusted PCCH multiplied by 365 and by projected population size. Then the projected quantity of net imports (exports) was subtracted (added). The resulting total projected production within the developing (developed) world was divided by its projected future crop yield per unit area to give the area required for the 23 crops, which we then expressed as a proportion of the area they occupied in 2000.

To explore the relative sensitivity of projected cropland area to changes in population size, PCCH, yield, and trade, we examined the effects of low, intermediate, and high projected values of each of these variables, for the developing and developed world in turn.

Results

Developing world

Plots of the estimated area needed under crops in 2050 (compared with that used in 2000) show that under most plausible projections, the land required to grow the 23 energetically most important food crops is set to expand in the developing world, but the extent of this increase is highly dependent on future population size, adjusted PCCH, and yield (Fig. 4a–c). For instance, at intermediate future levels of PCCH and trade (the middle blue curves in Fig. 4), and intermediate yield growth, developing-world area under the 23 crops need only increase by 2% above its year 2000 area if populations follow the UNPD low variant trajectory (Fig 4a). Under the same circumstances, medium variant population growth would require a 23% increase in area (Fig. 4b), and high growth would require a 49% increase

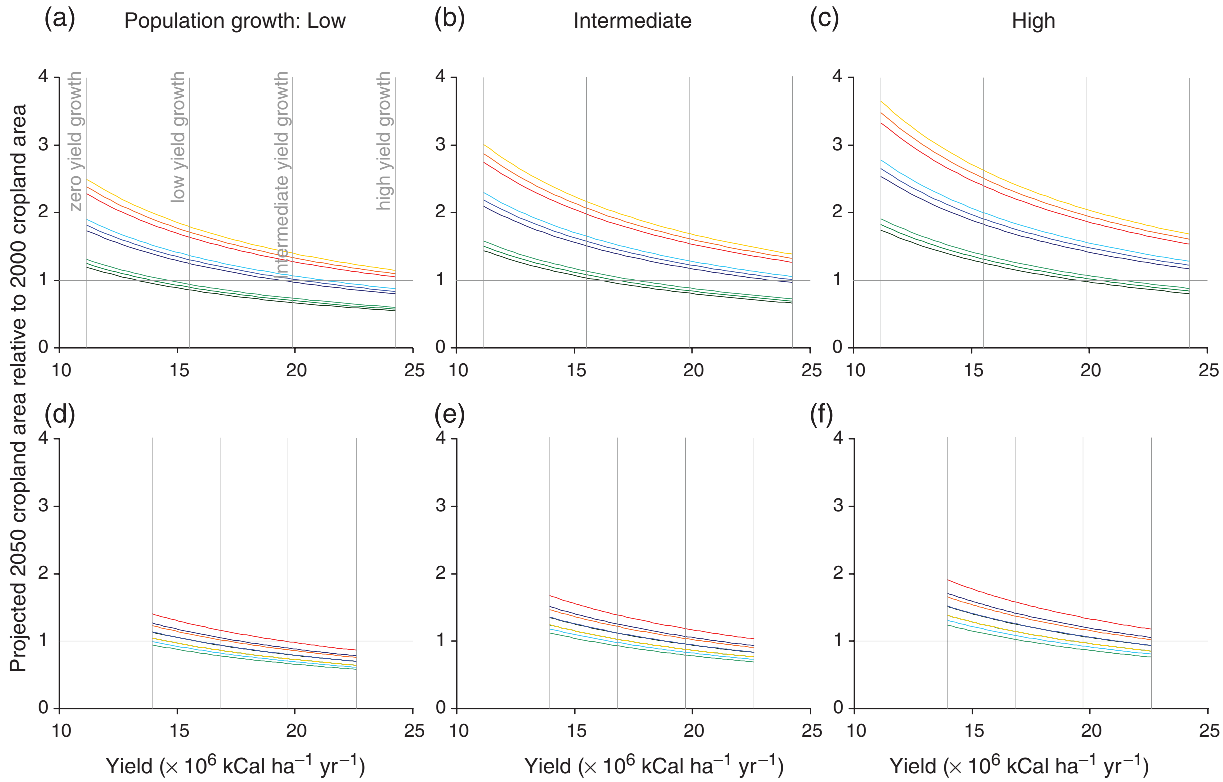

Fig. 4 Potential scope for land-sparing by 2050, showing proportional changes in the projected area of land needed (relative to the year 2000) to grow the 23 focal crops in the developing (upper panels) and the developed world (lower panels), as a function of projected yield, and under a range of projected values of population, per capita crop harvest (PCCH) , and trade. Population projections correspond to the UNPD's (2003) low (a,d), medium (b,e), and high (c,f) variants. Projections for developing-world trade-adjusted PCCH range from present-day developing world levels (green) through intermediate (blue) to present-day developed world levels (red). Projected net imports to the developing world are set at 5%, 10%, and 15% of total developing world production (indicated by increasingly dark lines). Projected yields correspond to growth ranging from zero to 1.5 times the linear growth rates seen from 1984 to 2000, with vertical lines depicting zero growth, and low, intermediate, and high growth projections. Note that in (d), (e) and (f), some curve overlap exactly.

(Fig. 4c). This sensitivity of developing-world cropland area to population growth (assuming intermediate values of all other variables) is further illustrated in Fig. 5a.

The effects of the range of PCCH values we considered is even more marked (Fig. 5a). For example, given intermediate values for projected population size, yield and trade, low PCCH could be met even with a 15% reduction in current area under the 23 crops (Fig. 4b, middle green curve), but high PCCH (middle red curve) would require a 61% expansion of their year 2000 area.

Future yield levels for the 23 energetically most important food crops are also likely to be extremely important (Fig. 5a): given intermediate population growth, PCCH and trade, low projected yield would require a 57% increase in the area under these crops from 2000 to 2050, whereas under high yield, the developing-world area need only expand by 1% (Fig. 4b, middle blue curve).

In contrast, changing the level of net imports from the developed world within a realistic range has far less impact on future developing-world cropland needs. Thus in Fig. 4a–c, all the same-coloured curves lie close together, while in Fig. 5a, under intermediate population growth, PCCH and yield growth, the change in area needed for the 23 crops from 2000 to 2050 varies only from +29% to +17% as net imports rise from 5% to 15% of developing-world production.

Developed world

By comparison with the developing world, projected changes in the developed-world area under the 23 crops are less marked and vary less with the projection used (Fig. 4d–f). Under many circumstances developed country cropland area is projected to continue to decrease, with plausible variation in population growth, future developing-world PCCH, yield growth and trade apparently having roughly equal consequences (Fig. 5b). Although the 2050 developed-world population varies little under different projections, net export of crops to

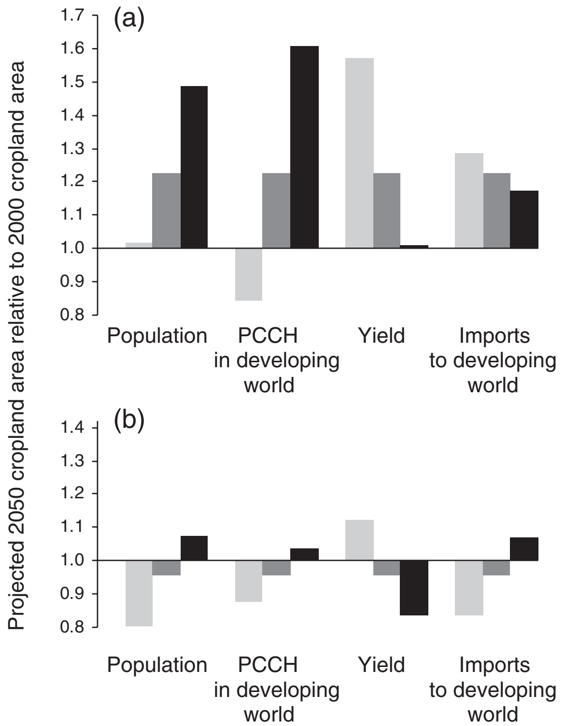

Fig. 5 Sensitivity of projected area of land needed to grow the top 23 crops in 2050 (relative to the year 2000) to projected variation in population size, trade-adjusted per capita crop harvest (PCCH), yield, and trade, for developing (a) and developed countries (b). For each variable in turn its projected value is set to low (light grey), intermediate (dark grey) and high levels (black), while all other variables are set to intermediate levels. Note that within a panel the dark grey columns have identical heights (because they each show the relative cropland needed when all variables have intermediate values).

help meet developing-world demand means that overall population growth does have some impact on future developed-world cropland needs (with area under the 23 crops shrinking by 20% under the UNPD low variant, but growing by 8% under the high variant, when all other variables are at intermediate values – Fig. 5b). The same reasoning applies to PCCH, where we have assumed no change in the developed-world values, but allowed PCCH to change in the developing world, which would affect the developed world through its exports. If PCCH in the developing world remains at current levels, the developed-world area under the 23 main crops would decrease by 2050 by 12%, but if developing-world PCCH rises to current developed-world levels then developed-world cropland area would increase by 4%, assuming intermediate population growth, yield, and trade (Fig. 5b).

Despite the fact that our projected yield values were less variable for the developed than the developing world, developed-world cropland area was more sensitive to developed-world yield than to any other variable (with future area under the 23 crops increasing by 12% or decreasing by 16% under low- and high-yield projections and intermediate values for other variables; Fig. 5b). Last, because total developed-world production is markedly lower than total developing-world production, plausible variation in trade has a greater impact on cropland area in the former, with our low trade projection associated with a 16% decrease in 23-crop area but the high trade projection requiring a 7% growth by 2050, assuming other variables attain intermediate values (Fig. 5b).

Discussion

The usefulness of our projections of cropland area depends upon how close they are to future reality. We have made projections of per capita food requirements, crop yields and trade, either by assuming that current levels will continue or that future levels can be estimated by extrapolating from regression models fitted to recent data. Hence, our findings are not predictions, but rather projections, assuming that recent patterns continue. They should be treated simply as an indication of what might happen under different sets of plausible circumstances, and hence as a device for exploring the relative leverage of different variables on the future area needed for crop production (and thus what may be left over for wild nature, and for other uses). Another important consideration is that because our approach requires conversion of crop production to a common currency of energetic value, we considered only the 23 energetically most important food crops. Ideally, we would make projections of total cropland area by using production, yield, and trade data for luxury and non-food crops too, but it is difficult to see how to project requirements for these in the way we have for energetically important crops. Our 23 focal crops account for more than half of all cropland area, but nevertheless trends in the area they occupy and their sensitivity to yield and other variables may not match those for other crops (especially given that these other crops include many more internationally traded crops such as coffee and cacao, as well as crops that are likely to be of growing importance for producing fuel or sequestering carbon). With these crucial caveats in mind, we believe our calculations nonetheless highlight a number of important points.

First, our projections suggest it is unlikely that global cropland area will decrease by 2050 (cf. Waggoner, 1995; Ausubel, 1996; Goklany, 1998; Waggoner & Ausubel, 2001). With all our variables set to intermediate levels, we calculate the global area needed in 2050 for the 23 main crops would be 14% larger than the area cultivated in 2000. We cannot make equivalent projections for cropland area as a whole, but we can suggest likely bounds. If trends in demand and yield of other crops are similar to those for our 23 focal crops, this would of course imply the 14% increase held for global cropland overall, but even in the extreme case of no increase in the area under these other crops, global cropland area would still have to increase by around 8% by 2050. However, these global averages mask important variation. In the developed world, low (or even slightly negative) domestic population growth, the assumptions of no net dietary change and limited trade, and the likelihood of sustained yield growth collectively mean that the area under our 23 crops is likely to decrease under most projections (e.g. when all variables are set to intermediate values we forecast a 4% contraction of 23-crop area). On the other hand, because of much higher population growth, sustained dietary improvements, and limits to feasible levels of imports, even though absolute yield growth is likely to be higher in the developing world, we expect the area need for the 23 main crops there to expand (for example, by 23% under intermediate projections).

Second, the extent of future population growth, change in developing country diet, and future yield growth, all look set to have a major bearing on future cropland needs, whereas variation in the export of crops from the developed world is likely to be less important (unless trade rises to levels which would be crippling to developing-country farmers – Conway & Toenniessen, 1999). The importance of population, diet and yield are underlined by considering real-world constraints on the amount of future cropland available. Most estimates are that more than half of all useable cropland is already in production. Young (1999) cautions that because of under-reporting of cropland area, overestimation of useable land, and failure to account for other land uses, the true figure for developing countries may be 75% or higher (see also Cassman *et al*., 2003). We have no data on how much the area specifically available for our 23 crops could plausibly be expanded, but if the figures for cropland as a whole are roughly indicative, this suggests that scenarios which require the developing-world 23-crop area to double by 2050 are probably not achievable. Both of our most extreme projections – of constant-fertility population growth (results not shown), and of zero-yield growth (Fig. 4) – require the area of the developing world needed for the 23 main crops to more than double by 2050 under a wide range of conditions. Perhaps more importantly, doubling or near-doubling is also required under many less extreme circumstances, such as when other variables are at intermediate levels but population and diet growth are both high, population or diet growth is high and yield growth low, or population and diet growth are both high and yield growth low (Fig. 4).

A third and related point illustrated by Fig. 4 is that there are likely to be important interactions between the effects of these key variables. For example, in either the developing or the developed world, the absolute potential scope for land-sparing through yield increases (illustrated by the vertical range of any one curve in Fig. 4) is greater when population growth is higher (compare corresponding curves in panels a–c), or when projected PCCH is higher (compare the vertical range of the red, blue, and green curves in any individual panel). Likewise the effect of increasing PCCH on cropland needs is greater under higher population growth (the separation of red, blue, and green curves is greater in panels c than a). A rather more subtle interaction is a negative one between the scope for future land-sparing and the area under cropland: as the area needed increases, cultivation will generally be forced to occupy more and more marginal lands, so that even retaining current average yields (let alone raising them and thereby reducing further conversion) will become increasingly difficult.

What are the implications of these findings for conservation scientists and practitioners? As a general point, the potential scope for land-sparing highlighted by our results suggests that as well as being concerned about population growth (a traditional interest), and growth in per capita consumption (an early and now growing concern – e.g. Ehrlich & Holdren, 1971; Myers & Kent, 2003), conservationists should be interested in patterns and consequences of changes in agricultural yield.

More specifically, we suggest that conservation scientists need to tackle three unanswered questions which would determine whether or not land-sparing through yield growth has an overall positive effect on wild nature:

1. Must yield increases on farmed land have disproportionate negative external effects on species and habitats on nonfarmed land? This would undermine benefits obtained from land-sparing and is a widely voiced concern about agricultural intensification (Conway, 2001; McNeely & Scherr, 2001; Pretty, 2002; Tilman *et al*., 2002). However, low input farming may also have negative effects on nonfarmed land (Avery, 1997), and though these may be lower per unit area of cropland, they may even exceed those imposed by higher yield farming in absolute terms if lower yields require much more area to be farmed (Ausubel, 1996, 2000). Clearly, more work quantifying the external effects of farming in relation to yield, and continued efforts to devise techniques which minimize them, are badly needed (Conway, 2001; Tilman *et al*., 2002; Mooney *et al*., 2005).

2. How do population densities of the species we are concerned about change as intact habitat is first converted to cropland and yields then increase? Recent modelling work suggests that whether the overall population of a species (and hence its probability of persistence) is higher under low-yielding but wildlife-friendly farming (with less nonfarmed land) or under less friendly, higher-yielding farmland (but with more land left unfarmed) depends critically on how its population density changes in response to increasing yield (Green *et al*., 2005). However, to date we know of no species for which these so-called density-yield functions have been derived.
3. To what extent does land spared from cropland become available for nature? There are several reasons for expecting that not all of the land potentially spared from agricultural use through yield increases will be conserved. For instance, if the demand for agricultural products or the supply of farm labour is elastic, or if technological changes free up rather than use up labour or capital, we might expect yield increases to lead to increased food production, which might result in some or all of the potentially spared land being used for agriculture (Angelsen & Kaimowitz, 2001). Likewise, land which is not needed for farming is often used in other ways that are unfavourable to wildlife. Despite that, there is some evidence that land-sparing does occur in practice. Regression analyses show that during the 1980s, developing countries with higher yield growth expanded their farmland area less, and those with higher crop yields cleared proportionately less of their tropical forest, than did other countries (Southgate, 1994; Barbier & Burgess, 1997). We believe there is a pressing need for more such studies, using larger sample sizes and more recent data, to explore how far and under what circumstances land is spared for wildlife as a consequence of increasing agricultural yields.

Our analyses have two other practical and topical implications for conservationists as a whole. In the developed world, our calculations suggest that yield increases, in combination with stable population size and per capita demand, are likely to mean that, in the foreseeable future, cropland area will continue to shrink. Recent reductions in farmland area have already facilitated ambitious and exciting programmes to recover wild ecosystems in Europe, North America, and elsewhere (Ausubel, 1996; Scott *et al*., 1999; Avery, 2001; Harvey, 2001; RSPB, 2001; Sutherland, 2002, 2004; Knight & Cowling, 2003). Appropriately managed yield increases mean such opportunities could proliferate over the next half-century, but they will not do so unless conservation practitioners are engaged actively in long-term planning of agricultural development and land use.

Finally, even if land-sparing has net beneficial effects on wildlife, it will not occur unless there is sustained yield growth without serious negative effects on biodiversity in nonfarmed areas. This in turn requires sustained investment in agricultural research and development, especially in developing countries (Binswanger *et al*., 1987; Craig *et al*., 1997; Evenson & Gollin, 2003). Conservationists should thus be concerned about the ongoing decline in public-sector funding of agricultural research in developing countries (Abelson, 1995; Avery, 1997; Ruttan, 1999; Tilman *et al*., 2002; Evans, 2003; Rosegrant & Cline, 2003). The potential benefits of yield increases also mean that conservationists should be both open-minded and actively engaged in the ongoing debate about genetically modified (GM) crops and other new agricultural technologies. These might benefit conservation in the developing world if they lead to yield increases and land-sparing or if they reduce negative effects on nonfarmed areas from fertilizers, pesticides and water abstraction. However, they could adversely affect conservation if they disproportionately reduce biodiversity on farmland, if they impose substantial negative externalities on wildlife elsewhere, or if they allow farming of biodiversity-rich land that is currently unsuitable for crops because of soils or climate. Even if possible beneficial effects on biodiversity of GM crops are realisable, they will not be of much help to conservation in biodiversity-rich parts of the world if they focus mainly on developed-world agriculture – our results show that improving yields of temperate crops will have little impact on cropland area in developing countries. However, if new agricultural technologies, including GM, can avoid the pitfalls described above and target developing-world subsistence crops and the needs and practices of developing-world farmers (Evans, 1997; Conway & Toenniessen, 1999; Conway, 2001; Pretty, 2002), it is possible that they could generate benefits for people and nature alike.

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