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Do increases in agricultural yield spare land for nature?

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Abstract

Feeding a rapidly expanding human population will require a large increase in the supply of agricultural products during the coming decades. This may lead to the transformation of many landscapes from natural vegetation cover to agricultural land use, unless increases in crop yields reduce the need for new farmland. Here, we assess the evidence that past increases in agricultural yield have spared land for wild nature. We investigated the relationship between the change in the combined energy yield of the 23 most energetically important food crops over the period 1979–1999 and the change in per capita cropland area for 124 countries over the same period. Per capita area of the 23 staple crops tended to decrease in developing countries where large yield increases occurred. However, this was counteracted by a tendency for the area used to grow crops other than staples to increase in the countries where staple crop yields increased. There remained a weak tendency in developing countries for the per capita area of all cropland to decline as staple crop yield increased, a pattern that was most evident in developing countries with the highest per capita food supplies. In developed countries, there was no evidence that higher staple crop yields were associated with decreases in per capita cropland area. This may be because high agricultural subsidies in developed countries override any land-sparing pattern that might otherwise occur. Declines in the area of natural forest were smaller in countries where the yield of staple crops increased most, when the negative effects of human population increases on forest area were controlled for. Our results show that land-sparing is a weak process that occurs under a limited set of circumstances, but that it can have positive outcomes for the conservation of wild nature.

Keywords: agricultural intensification, deforestation, food availability, global analysis, land use change

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Introduction

Thomas Malthus made a famous prediction that human population growth would outstrip food supply by the middle of the 19th Century (Malthus, 1798). The catastrophe that Malthus predicted did not materialise, but the question of how best to feed an expanding human population with rising per capita expectations remains highly relevant. While agricultural production systems may be able to meet the expected doubling of global demand for food by the year 2050 (Plucknett, 1993; Waggoner, 1995; Tilman *et al*., 2002; Balmford *et al*., 2005), what will be the cost to nature? One possibility is that increases in crop yield will result in land-sparing: a reduction in the amount of new cropland area that would otherwise be required to meet increased demand, allowing, though not ensuring, a greater area of intact habitat to be spared from conversion to agriculture (Balmford *et al*., 2005). Land-sparing has become an important issue in reconciling biodiversity conservation with sustainable development (Balmford *et al*., 2005; Green *et al*., 2005; Mattison & Norris, 2005; Matson & Vitousek, 2006). Many believe that, given growing

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human needs, improvements to agricultural yields represent the best prospect for limiting the impact of farming on remaining natural habitats (Brubaker, 1977; Angelsen & Kaimowitz, 1998).

Agricultural yields have risen dramatically over the last 40 years (Waggoner, 1995; Matson *et al*., 1997; Goklany, 1998; Balmford *et al*., 2005; Green *et al*., 2005), giving rise to a prediction that growing food demands for the foreseeable future can be met while at the same time reducing the total amount of agricultural land (Waggoner, 1995). However, this might be unduly optimistic: cropland area has expanded in recent times (Donald, 2004; Green *et al*., 2005). Despite rapid increases in crop yield, global cropland area is likely to expand even further by 2050 (Balmford *et al*., 2005). Even so, increasing yields from technological innovations have been credited with avoiding the need to convert large areas of uncultivated land across the planet (Goklany, 1998; Barbier, 2004; Mooney *et al*., 2005).

Critics of the land-sparing hypothesis raise three broad arguments to suggest that it may not provide real benefits for conservation (Matson *et al*., 1997; Matson & Vitousek, 2006; Morton *et al*., 2006; Vandermeer & Perfecto, 2007): (1) that the on-farm losses of biodiversity due to high-yielding agriculture outweigh the benefits of sparing habitats from conversion; (2) that high-yielding agricultural systems have negative external effects on biodiversity away from farmland; and (3) that land-sparing does not occur or is imperfect, so that an increase in crop yield does not lead to a proportionate increase in the area of land available for nature.

The first of these arguments is motivated by observations that intensification of farming often leads to negative effects on biodiversity within the farmed landscape. For example, cereal yield increases in Europe are associated with population declines and range contractions of numerous farmland birds (Donald *et al*., 2001), and rare Mediterranean plants have been more prone to local extinction in sites where agricultural land use has intensified over the last 100 years than elsewhere (Lavergne *et al*., 2005). Many believe that the adoption of wildlife-friendly farming techniques would benefit biodiversity (Mattison & Norris, 2005; Vandermeer & Perfecto, 2007). However, insofar as these methods decrease farm yields, whether they would result in a net gain for conservation depends upon a trade-off between biodiversity losses on the natural lands that would be consumed by the expansion of low-yielding agriculture and on-farm biodiversity gains arising from the transition from high- to low-yielding agriculture. A model to quantify this trade-off, based on a preliminary survey of the few data available, indicated that most species would benefit more from high-yield farming and land-sparing (Green *et al*., 2005), although they recognised that this result might vary across taxa and farming systems, and depend as well on historical patterns of land-use.

The second argument stems from observations that high-yielding agriculture can adversely affect the abundance of wild species outside farmed areas. Off-farm environmental impacts include pollution of aquatic habitats and groundwater (Matson *et al*., 1997; Tilman *et al*., 2002), diversion of water supplies affecting downstream regions (Matson *et al*., 1997), and reliance on chemical inputs whose manufacture and use produce greenhouse gases (Chameides *et al*., 1994; Matson *et al*., 1997). Agricultural intensification can also increase rates of deforestation in surrounding landscapes if agricultural mechanisation is correlated with mechanisation of the forest-clearing process (Morton *et al*., 2006).

The third objection to land-sparing is that increases in yield do not save land from conversion to agriculture – or at least not enough to offset the negative effects of high-yield farming. There are at least three possible reasons for this:

(a) High-yield farming may free up labour, increase capital, increase demand, or increase farm profit margins, and thereby stimulate increased production (Angelsen & Kaimowitz, 1998). For example, Angelsen *et al*. (1999) showed that increasing yields in Tanzanian agriculture tends to encourage existing farmers to expand their farms. Similar results have been found for regional-scale analyses of agricultural systems in the Brazilian Amazon (Vosti *et al*., 2001) and western Africa (Ruf, 2001), but are countered by examples such as banana-growing in Ecuador, where increased yield combined with a steady global market has reduced the need for further cropland expansion (Wunder, 2001). Labour-saving advances may displace people from existing farms into the surrounding area where they set up their own farms (Angelsen & Kaimowitz, 1998; Matson & Vitousek, 2006), but the reverse may also happen if labour-intensive advances create better employment opportunities drawing people into a smaller area of high-intensity farmland (Shively & Pagiola, 2004).

(b) Government subsidies may override the classical economic constraints of demand and supply to such an extent that increased yields lead to a surplus of agricultural products, rather than reductions in production and hence total farmed area (Koo & Kennedy, 2006; La Vina *et al*., 2006). Most countries have some form of subsidy to protect their agricultural sector (Koo & Kennedy, 2006), and these often stimulate over-production (Benton, 2007).

Government-subsidised credit to cattle ranchers in the Brazilian Amazon has contributed to the rapid expansion of the industry in the last 15 years (Barreto *et al*., 2006), agricultural subsidies in Costa Rica promoted forest clearance to provide more cropland in the 1970s and 1980s (Brockett & Gottfried, 2002), and subsidies in the United States have led to vast crop surpluses (Koo & Kennedy, 2006).

(c) Land spared from agriculture may be used for purposes which do not benefit wild species. As Matson & Vitousek (2006) rightly point out, to have a conservation benefit, land-sparing must result in a decrease in the rate of conversion of natural land.

Previous empirical studies of land-sparing have been case studies or restricted to particular regions (see Angelsen & Kaimowitz, 2001). These suggest that across tropical landscapes, increasing yields can either increase or decrease deforestation rates depending on the local conditions and whether the technology was labour-intensive or labour-saving (Roebeling & Ruben, 2001; Ruf, 2001; Vosti *et al*., 2001; White *et al*., 2001; Wunder, 2001; Van Soest *et al*., 2002; Shively & Pagiola, 2004). At a larger scale, an analysis of 53 tropical countries suggested that the net effect of increasing agricultural yields was to decrease rates of tropical deforestation (Barbier & Burgess, 1997). However, to date there has been no global assessment of land-sparing. In this paper, we examine global patterns of change in agricultural yields and cropland extent over a 20-year period. We assess changes in crop yields for the world's 23 energetically most important food crops (staple crops) and relate those to changes in the area occupied by cropland. We make no attempt to quantify the role of externalities in reducing the potential conservation gain from land-sparing, but do assess the strength of the three arguments against the degree of perfection of land-sparing by (1) controlling our analysis for variables that may alter the demand for food products, such as differences in population size and food availability; (2) investigating global patterns of agricultural subsidies and (3) relating global changes in yield directly to changes in the extent of natural forest, a habitat type of particular relevance to nature conservation. Our results give a first indication of the potential for, and realisation of, conservation gains from land-sparing at a global level.

Materials and methods

Relationship of change in cropland area to yield change

We analysed crop production and cropland area for all 124 countries with usable data in *FAOSTAT* (FAO, 2001a). FAO crop data are strongly criticised for containing inconsistencies among countries in reporting dates and in methods of estimating yields, outputs and area of farmland (Gill, 1993; Young, 1998), but are nonetheless the only global data available (Balmford *et al*., 2005). Data inconsistencies are liable to reduce the strength, and therefore the statistical significance (Young, 1998), of any observed relationships but seem unlikely to have generated spurious correlations. Countries were categorised as 'more' or 'less' developed, using the FAO definition (which differs slightly from the United Nations definition – Balmford *et al*., 2005), and are hereafter referred to as 'developed' and 'developing' countries. To allow for the breakup during our 1979–1999 study period of the Soviet Union (now represented by 16 independent countries), Yugoslavia (6) and Czechoslovakia (2), crop data in 1999 from the new states were summed to obtain values directly comparable to the 1979 data for the original three countries. Thus, these 24 countries are merged to just three, which we treat as countries.

We obtained data on production (harvested mass in tonnes) of the world's 23 energetically most important food crops, hereafter referred to as staple 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 staple foods and represent 60% of the global total harvested tonnage in 2000 (Balmford *et al*., 2005). Crop production was converted from mass to energetic equivalents (kcal) (after Balmford *et al*., 2005). Crop yield was calculated for all countries in 1979 and 1999 as the total energetic production of the 23 crops divided by the sum of the area (ha) under those crops in those countries in that year. We refer to this throughout the paper as yield. Three aspects of cropland area (ha) were examined: (i) the area under the 23 staple crops; (ii) the area of cropland devoted to farming of other, nonstaple, crops and (iii) the total area of cropland, which is the sum of the first two. We allowed for the effect of changes in human population by dividing crop area by the population size (also obtained from *FAOSTAT*) of each nation in each year. We refer to this as per capita cropland area.

We calculated changes over time (Δ) in these variables by combining the 1979 and 1999 values to create the dimensionless quantities $\Delta = \log\ [\text{value}_{1999}/\text{value}_{1979}]$. For brevity, we refer to these log ratio values elsewhere as change in yield or per capita cropland area. We fitted ordinary least squares regression models with change in per capita cropland area as the dependent variable and change in yield as the independent variable. Our expectation is that, if land-sparing occurs, the change in per capita cropland area will be negatively related to the change in yield. If land-sparing is perfect, this relationship would be represented by a straight line with slope -1 and intercept zero. The direction of this effect for the area of cropland used to grow staple crops and for all crops is clearly specified *a priori*, so one-tailed statistical tests are appropriate. For the area of nonstaple crops, the expected direction of the effect of change in yield of staple crops depends upon whether or not the changes in agricultural practice, which drive the yield change, free up labour or capital for other kinds of agricultural enterprises. For this reason, we performed a two-tailed test of the effect of change in yield of staple crops on per capita area of nonstaple crops.

We anticipated that the strength of land-sparing might be modified by two effects. First, we expected agricultural subsidies to distort land-sparing by providing incentives for production beyond those arising from the needs of the human population of a country for basic foodstuffs. We obtained data from the World Trade Organisation on national agricultural subsidies in US$ per hectare of cropland in 1999 (http://www.ers.usda.gov/db/wto/). Ideally, we would have included the level of subsidy per hectare of cropland for each country in the analyses. However, this was not possible because subsidy data were available for just 31 countries. Hence, we restricted the analysis to a comparison of average subsidy levels among the country groupings used in the regression analysis. Our expectation is that the strength of the land-sparing effect (as represented by the negative relationship between change in per capita cropland area and change in yield) will be greatest within those groups of countries with the lowest subsidy levels.

The second effect expected to modify land-sparing occurs where basic foods are in short supply. In such cases, we expected that increases in the yield of staple crops might not be sufficient to meet the needs of the country's population, and hence the pressure to increase cropland area would not diminish. To test for this effect, we included the daily per capita food supply (kcal, referred to as food supply) at the beginning of our study period (1979) in the analysis (World Resources Institute, 2007), both as a main effect and as an interaction term together with yield change. Our expectation is that increasing food supply would increase the strength of the land-sparing effect, which would appear as a negative coefficient for the food supply $\times$ yield change interaction in the regression model. We also examined this hypothesis by testing the relationship between change in per capita cropland area and change in yield separately for three categories comprising the lowest, middle and highest third of developing countries ranked according to food supply in 1979.

Relationship of change in natural forest area to yield change

We assessed the degree to which land spared from agriculture results in land being spared for nature using data on forest cover change from 1980 to 2000, obtained from the *Forest Resource Assessment 2000* (FAO, 2001b); this period closely matches that for the crop data (1979–1999). Forest is just one of many forms of natural land cover that might benefit from land-sparing, and was selected for analysis because it is the only natural land cover for which data on change in extent exist at the global scale. Forest change data from the *FRA2000* have been criticised for being variable in quality across countries and for inconsistencies in definitions (Barbier & Burgess, 2001; Rudel *et al*., 2005; Grainger, 2008), likely overestimate actual forest loss compared with estimates from remote sensing (Achard *et al*., 2002), but remain the sole comprehensive source of national deforestation rates (Matthews, 2001; Ewers, 2006). Total forest cover is presented in the *FRA2000*, with the component of it that is plantation also identified. We calculated the area of natural forest as total forest minus plantation forest (Matthews, 2001). Change in natural forest area was calculated as the log ratio of natural forest area in 2000 to that in 1980.

We inspected the data for 1990, as well as for 1980 and 2000, and noticed implausibly rapid changes during some 10-year periods in the proportion of total forest that was natural. Because these rapid changes in proportion were not associated with large changes in total forest area, it appeared that they were probably due to changes in the definitions used in compiling statistics for natural or plantation forests (Matthews, 2001). For this reason, we excluded all data from countries in which the statistics showed a halving or doubling, or a more extreme change, in the proportion of natural forest during a 10-year period. This screening resulted in the exclusion of data for five countries.

We investigated the association between change in natural forest area and change in yield by ordinary least squares regression analysis. To allow for the expected confounding effects of change in human population size, we also included in the regression the log ratio of population size in 1999 compared with 1979. We tested for effects of food supply on the strength of land-sparing by including it and its interaction with change in yield in the model. We expect the effect of yield change on change in natural forest area to be positive, the effect of change in human population to be negative, and the interaction of food supply and yield change to be positive, so we used one-tailed significance tests of these effects. There were 115 countries with data available for these variables; 90 developing and 25 developed countries.

Results

Relationship of cropland area change to yield change

When all countries were considered together, there was weak evidence for land-sparing. The regression coefficient of change in per capita cropland area used for the 23 staple crops regressed on change in yield was negative, but substantially less negative than the value of -1 that was expected if perfect land-sparing was occurring ($b = -0.143$, $t = -1.92$ $P = 0.029$). The equivalent analysis with change in per capita area of all cropland as the dependent variable also gave a negative, but even weaker, relationship ($b = -0.054$, $t = -0.70$, $P = 0.243$). However, the majority (87 out of 96 countries) of countries that increased yields over the 20-year period also reduced their total per capita cropland area. The weaker effect for change in total cropland area than for cropland used to grow staple crops suggests that increase in yield of staple crops might be associated with increase in area of nonstaple crops. We found that the change in per capita cropland area of nonstaple crops correlated positively, although not significantly, with change in yield of staple crops ($b = 0.189$, $t = 1.07$, $P = 0.287$).

The overall weakness of observed land-sparing might, at least in part, be due to agricultural subsidies distorting land use decisions. Because our data on subsidies were incomplete, we cannot test directly for the possible effect of subsidy level by including it as a variable in a multiple regression analysis. However, comparisons between those developed and developing countries with data available show that subsidy levels (in US\$ ha^{-1} yr^{-1}) were significantly higher in developed than in developing countries (Mann–Whitney *U*-test; $U = 69$, $P = 0.039$; Fig. 1). This suggested that a way to allow for the effect of agricultural subsidies is to perform the regression of change in cropland area on change in yield separately for developing and developed countries. Our expectation is that the effects of land-sparing should be seen more clearly in developing than developed countries because subsidies are at very low levels in the former group.

As expected, the negative relationship between change in the per capita cropland area growing staple crops and change in yield was stronger and statistically significant for developing countries ($b = -0.152$, $t = -1.78$, $P = 0.040$) and weaker and non-significant for developed countries ($b = -0.089$, $t = -0.57$, $P = 0.289$).

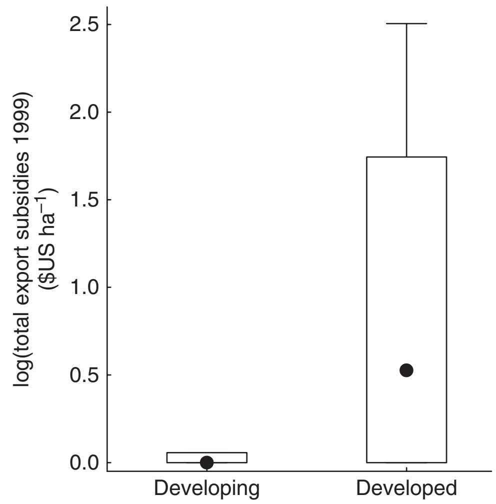

Fig. 1 Comparison of annual agricultural subsidies per unit area of cropland between developing and developed countries. Results are shown separately for 18 developing and 13 developed countries. Circles represent medians, boxes the interquartile range and whiskers the nonoutlier range.

However, the slopes were not significantly different for developed and developing countries (*t*-test; $t_{120} = 0.35$, $P = 0.363$). The relationship between change in total per capita cropland area and change in yield was negative, although not significant for developing countries ($b = -0.082$, $t = -0.99$, $P = 0.163$), but positive in developed countries ($b = 0.157$, $t = 0.70$, $P = 0.246$), contrary to the prediction from land-sparing. Again, the difference in slopes was not significant ($t_{120} = 1.00$, $P = 0.160$). The difference between developing and developed countries in the results for total cropland area reflects a significantly greater tendency in developed countries for the per capita area of nonstaple crops to increase with increases in yield (developed countries: $b = 1.003$, $t = 2.08$, $P = 0.047$; developing countries: $b = 0.091$, $t = 0.49$, $P = 0.624$; difference in slopes: $t_{120} = 1.77$, $P = 0.040$).

A possible reason for the weak evidence for land-sparing in developing countries is that it is only likely to occur where food supply is reasonably high. To test for this, we repeated the regression analysis of change in per capita cropland area on change in yield of staple crops for developing countries only, and included the main effect of per capita food supply in 1979 and its interaction with change in yield. The interaction term between food supply and yield change was negative, as expected under this hypothesis, and approached statistical significance for the analysis with change in per capita area of cropland growing staple crops as the dependent variable ($t_{91} = -1.61$, one-tailed $P = 0.056$). With change in per capita total cropland area as the dependent variable, the interaction was still negative, but nonsignificant ($t_{91} = -0.94$, one-tailed $P = 0.175$). The difference in the strength of the food supply × change in yield interaction between staple and per capita total cropland area arose because of a highly significant positive interaction between food supply and change in yield when the change in per capita area of nonstaple crops was the dependent variable ($t_{91} = 2.72$, two-tailed $P = 0.008$). We performed a two-tailed test of this interaction because we did not anticipate its sign *a priori*.

We illustrate these relationships by plotting graphs of change in per capita cropland vs. change in yield for developing and developed countries separately and by dividing the developing countries into thirds on the basis of 1979 food supply (Fig. 2). The third of developing countries with the highest food supply exhibited a significant, negative relationship both between change in yield and in per capita cropland area devoted to staple crops ($t_{29} = -2.23$, $P = 0.017$) and between change in yield and change in per capita total cropland area ($t_{29} = -2.03$, $P = 0.03$; Figs 2 and 3). Developed countries had a significant, positive relationship between change in per capita cropland area devoted to nonstaple crops and change in yield ($t_{29} = 2.08$, $P = 0.047$). All other relationships were nonsignificant ($P > 0.05$).

Relationship of change in natural forest area to yield change

We anticipated that, if land-sparing did occur, changes in natural forest area would be positively related to change in crop yields. Because growth in human population would be expected to increase the demand for staple crops and the requirement of cropland, we also expected that change in forest area would be negatively related to change in human population. Both of these

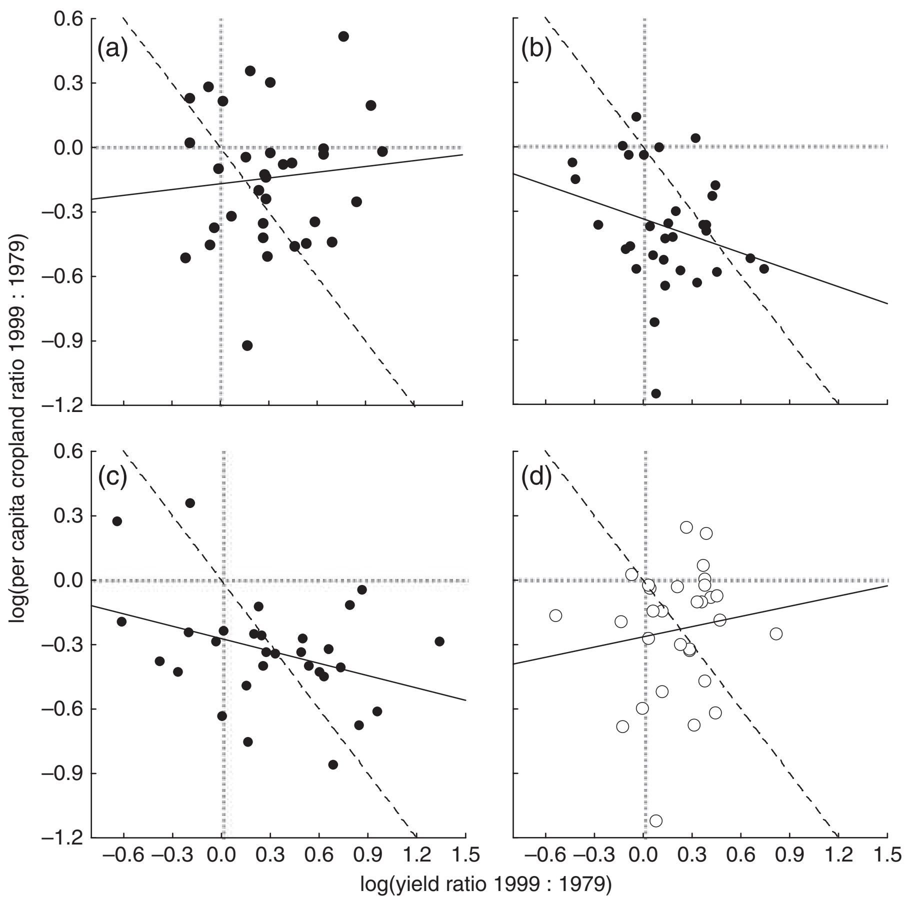

Fig. 2 Change in the per capita area of all cropland during the period 1979–1999 in relation to the change in energy yield per unit area of the world's 23 most energetically important staple food crops during the same period. Results are plotted separately for the (a) lowest, (b) middle and (c) highest third of developing countries ranked according to daily per capita food supply in 1979, and (d) for developed countries. Solid lines are from least squares linear regression models fitted to the data; dashed lines show the relationship expected if perfect land-sparing occurred. Dotted grey lines divide the graphs into four quadrants; countries located in the bottom right quadrant exhibited land-sparing in that cropland area decreased as yield increased.

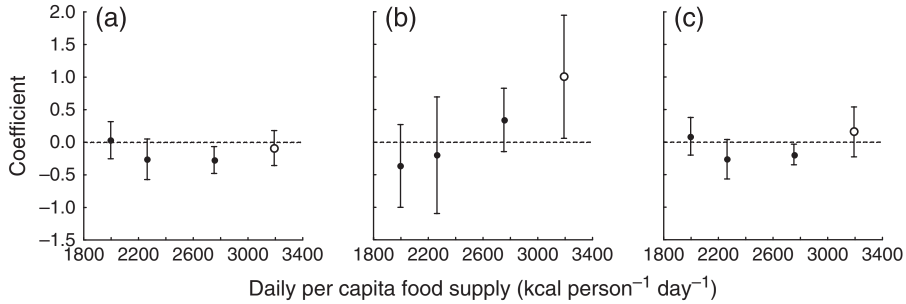

Fig. 3 Regression coefficients for the relationship between the 1979 and 1999 change in energy yield per unit area and change in per capita cropland area of (a) the world's 23 most energetically important crops, (b) other crops and (c) all crops combined. Values for (c) are obtained from the data presented in Fig. 2, and are plotted against the mean daily per capita food supply in 1979. Error bars in (a) and (c) are 90% confidence limits, reflecting the one-tailed tests used for these analyses; error bars in (b) are 95% confidence limits. Values less than zero (dashed line) indicate land-sparing, with a value of −1 representing perfect land-sparing. Filled circles = developing countries; open circles = developed countries.

expectations were confirmed by the multiple regression analysis of change in natural forest area between 1980 and 2000 in relation to change in yield and change in human population. The multiple regression coefficient of forest change on yield change was significantly positive ($t_{112} = 2.32$, $P = 0.011$) and that for human population change significantly negative ($t_{112} = -4.26$, $P < 0.0001$).

Because of the potential confounding effect of agricultural subsidies, we performed this multiple regression analysis separately for developed and developing countries. We expected that the evidence for land-sparing would be stronger in developing countries than in developed countries because of the lower levels of agricultural subsidies in developing countries. Both developing and developed countries had the predicted significant positive relationship between change in natural forest cover and change in yield (developing: $t_{87} = 1.80$, $P = 0.038$; developed: $t_{22} = 1.71$, $P = 0.050$) and the effect of human population change was, as expected, negative in both country groups (developing: $t_{87} = -1.43$, $P = 0.078$; developed: $t_{22} = -2.12$, $P = 0.023$). However, the regression coefficient for yield change was more positive for developed than developing countries (0.532 cf. 0.360), which was contrary to expectation, although the multiple regression relationships did not differ significantly between developing and developed countries ($F_{3,109} = 0.86$, two-tailed $P = 0.462$).

To illustrate the relationship between change in natural forest area and change in yield, we plotted graphs of change in natural forest area, adjusted for change in human population, against change in yield (Fig. 4). We adjusted the observed change in natural forest area to that expected after allowing for the growth in human population between 1979 and 1999, by taking the residuals from a regression of change in natural forest area in response to change in population. The graph shows

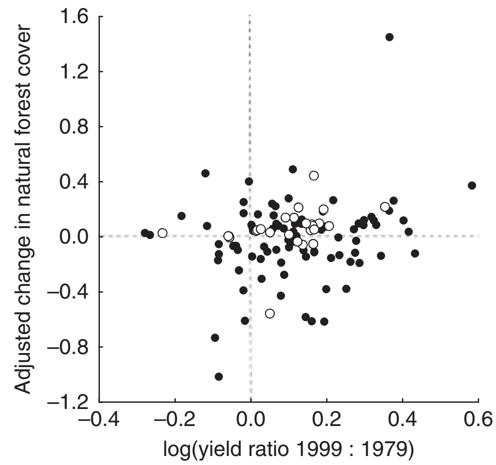

Fig. 4 Change in the extent of natural forest cover, adjusted to that expected given the observed change in human population size, for developing (filled circles) and developed (open circles) countries in relation to the change in the yield of staple crops. Change in forest area is for 1980–2000, whereas change in yield is for 1979–1999. Each point represents the value for a country. Dotted grey lines divide the graph into four quadrants; countries located in the top right quadrant had the predicted result in that forest cover increased as yield increased.

that, after allowing for variation in population growth, natural forest area tended to decline in countries where the yield declined or did not increase, whereas forest area fell by a smaller proportion in countries with substantial yield increases (Fig. 4).

Finally, we tested the effect of food supply in 1979 on the strength of these relationships by including in the model, together with change in yield and change in human population, the main effect of food supply and its interaction with change in yield. This model permitted us to test whether the slope of the relationship between change in natural forest area and change in yield was altered with changing food supply among countries. Our expectation was that this slope should become more positive (i.e. more evidence of land-sparing) as food supply increases. We found only a weak indication of the expected positive interaction ($b = 0.0004$, $t = 0.929$, $P = 0.177$).

Discussion

The rapid growth of the human population has led many conservationists to believe that harmonising food production with conservation is all but impossible (Matson & Vitousek, 2006). However, one process that could reduce pressure on natural habitats in future is meeting the increasing global food demand, at least in part, by increasing agricultural yields rather than simply through expansion of cropland. Our results show that rising demand for food products from an expanding population and the perverse effect of agricultural subsidies, while they have been accompanied by increases in cropland area, have not completely cancelled out the land-sparing effect of increased yield of staple food crops. Moreover, some of the land spared from conversion to agriculture appears to have remained valuable for wild nature, as indicated by the lower rate of loss of natural forest in countries with large increases in yield of staple crops. Hence, in terms of land cover, it appears that rising staple crop yields have provided some benefits for global nature conservation.

However, our evidence for land-sparing effects of increased crop yield was uneven. The per capita area of cropland used to grow staple crops increased by a significantly smaller proportion in developing countries where staple crop yield increased, but this effect was not found in developed countries. We suggest that this difference might be due to distortions of agricultural land use decisions caused by agricultural subsidies, which are considerably higher per unit area of cropland in developed than developing countries. Subsidies may disconnect farm outputs from market demand, leading to the accumulation of agricultural surpluses rather than a reduction in the area of farmed land (Myers & Kent, 2001).

Even in developing countries, which have lower levels of subsidies, we found that the land-sparing effects of increases in staple crop yield, though suggested by a negative regression coefficient, were not statistically significant when the change in per capita area of all crops was considered. This was because the per capita area of crops other than staple crops tended to increase with increasing staple crop yield. This might occur if technological change that increases yields of staple crops frees up labour or capital to permit the growing larger areas of other crops. Such effects would obviously reduce or cancel out beneficial effects of staple crop yield increases on the area spared for natural habitats.

We hypothesised that one factor that might weaken a tendency for yield increases to spare land for nature would be if increases in the yield went to reduce unmet needs of the population for food, rather than reducing the land required for staple food production. Our tests for this, by including food supply in our regression models for developing countries, produced equivocal results. The effect of food supply on the strength of the land-sparing effect was in the expected direction; land-sparing was more evident in developing countries with high food supply. However, the effect was of marginal statistical significance, probably because of the countervailing tendency, noted above, for yield increases to be associated with increases in the area of nonstaple crops, a pattern that was also stronger in developing countries with relatively high food supply. Nonetheless, there was a significant tendency for the change in per capita area of both staple crops and all crops to decline with increased yields of staple crops in the third of developing countries with the highest per capita food supply. In contrast, there was no indication of an effect of food supply on the strength of the relationship between staple crop yield change and change in the area of natural forest.

There appeared to be a weak, positive impact of increases in yield on natural forest cover. We focussed on forest cover in this study because it is the one form of natural land cover for which global data are available and which is also known to support substantial biodiversity (Millennium Ecosystem Assessment, 2005). However, we recognise that forests are just one of many natural ecosystems threatened by agricultural expansion around the world. Because land that is spared from agricultural use may potentially retain these other natural landcover types, we did not necessarily expect to find strong relationships between changes in yield and changes in forest cover. Consequently, it is encouraging that the effect was detectable. Our result mirrors that of Barbier & Burgess (1997), who discovered that deforestation rates were reduced in tropical countries with high growth in agricultural yields. This suggests that the conservation benefits of land-sparing have, in the past, been general and consistent, at least in developing countries.

Will agricultural yield increases continue to provide benefits, albeit weak benefits, by sparing land for wild nature in the future? Given that crop yields are increasing less rapidly than they were a decade ago (Tilman *et al*., 2002; Balmford *et al*., 2005), we suggest that this will depend on a tension between new and rising demands for agricultural products, and conservationoriented changes to government policies. Two emerging markets for agricultural products threaten to create new sources of demand that may increase conversion of natural land cover for farming and reduce or eliminate any positive effects gained from land-sparing. The first is that increasing affluence is correlated with a dietary shift to include a higher proportion of meat (Tilman *et al*., 2002; Myers & Kent, 2003). Much of the livestock produced for food markets is grain-fed (Tilman *et al*., 2002; Myers & Kent, 2003; Nepstad *et al*., 2006), exerting a strong demand for increased amounts of cropland. Grain for animal feed occupies one-third of all cropland in the United States (Waggoner & Ausubel, 2002), and a dietary shift to include more meat requires a larger cropland area to maintain food supply than if the grain was consumed directly (Pimentel & Pimentel, 2003). Consequently, rapid wealth increases in developing countries, including populous countries such as China and India, have the potential to greatly increase the demand for cropland around the world (Myers & Kent, 2003).

The second emerging market of great concern is biofuels. While these are receiving enormous attention as part of the global search for strategies to mitigate anthropogenic carbon emissions, they will require extensive areas of agricultural land to have a noticeable influence on fossil fuel emissions (Righelato & Spracklen, 2007; Scharlemann & Laurance, 2008). Rapid growth in demand for ethanol-powered cars has seen Brazil's ethanol production from sugarcane expand almost 50% between 2001 and 2005, and it is expected to almost double again by 2010 (Marris, 2006). The expansion of the biofuel industry is also predicted to swallow up large expanses of agricultural land in Europe over the next 20 years (Eickhout *et al*., 2006).

On the other hand, there are several political processes underway that may counteract the rising demand for agricultural land. One is the much-debated option of including payments for avoided deforestation into the Clean Development Mechanism of the Kyoto Protocol (Pfaff *et al*., 2000; Maréchal & Hecq, 2006; Teixeira *et al*., 2006; da Fonseca *et al*., 2007; Gullison *et al*., 2007; Laurance, 2007). The motivation here is to limit the emission of carbon dioxide from deforestation, which is currently responsible for 15–20% of all global carbon emissions (DeFries *et al*., 2002; Gullison *et al*., 2007). The key feature of avoided deforestation programmes in the present context is that they may increase the monetary value of standing forests such that the opportunity cost to landowners from clearing land for crops is increased. By altering the relative profitability of land conversion, payments for avoided deforestation may offset demand-driven price increases for agricultural commodities. For now, the exact effects of an avoided deforestation policy remain speculative, but encouraging political movements from tropical countries show that the policy itself is moving steadily closer to becoming reality (UNFCC, 2005; Laurance, 2007).

Another encouraging process that may enhance the conservation benefits of land-sparing is the restructuring of agricultural subsidies to explicitly incorporate biodiversity goals. Our results are indicative, although not conclusive, that production-based subsidies may have diluted a land-sparing effect in developed countries. There are several indications that past negative effects of subsidies on natural environments in developed countries are beginning to dissipate or even reverse. Some countries, such as New Zealand, have steadily removed their provision of subsidies (Mattison & Norris, 2005) with consequent changes to land use patterns (Swaffield & Primdahl, 2006). In the much larger economic entities of the United States and the European Union (EU), the central goal of subsidies has, in some cases, been altered to reflect the environmental aspirations of society at large. Widespread evidence of biodiversity declines in agroecosystems in Europe has been used to justify agri-environment payments of more than $2.7 billion to farmers in the EU every year through the Common Agricultural Policy (European Environment Agency, 2002), and of similar amounts in North America (Benton, 2007). These schemes (which include payments for retiring land from production) are expensive, but may carry substantial benefits for natural habitats (Donald & Evans, 2006).

Land-sparing is not a panacea for conservation, but our analysis shows that in the past it may have contributed to the maintenance of natural vegetation cover; an assertion that is supported by a small number of empirical studies at regional scales (Barbier & Burgess, 1997; Grau *et al*., 2008). Such benefits as have been gained were obtained even in the face of growing human populations. Whether land-sparing will lead to conservation benefits in the future is a matter of debate. We believe that conservation biologists should be open-minded about the potential benefits for the conservation of wild nature that advances in agricultural technology may permit. However, our analyses suggest that the mechanisms by which land use policy influences the persistence of natural habitats will need to change if the potential gains are to be realised.

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