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Report

Long-Term Global Trends in Crop Yield and Production Reveal No Current Pollination Shortage but Increasing Pollinator Dependency

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Summary

There is evidence that pollinators are declining as a result of local and global environmental degradation [1–4]. Because a sizable proportion of the human diet depends directly or indirectly on animal pollination [5], the issue of how decreases in pollinator stocks could affect global crop production is of paramount importance [6–8]. Using the extensive FAO data set [9], we compared 45 year series (1961–2006) in yield, and total production and cultivated area of pollinator-dependent and nondependent crops [5]. We investigated temporal trends separately for the developed and developing world because differences in agricultural intensification, and socioeconomic and environmental conditions might affect yield and pollinators [10–13]. Since 1961, crop yield (Mt/ha) has increased consistently at average annual growth rates of ~1.5%. Temporal trends were similar between pollinator-dependent and nondependent crops in both the developed and developing world, thus not supporting the view that pollinator shortages are affecting crop yield at the global scale. We further report, however, that agriculture has become more pollinator dependent because of a disproportionate increase in the area cultivated with pollinator-dependent crops. If the trend toward favoring cultivation of pollinator-dependent crops continues, the need for the service provided by declining pollinators will greatly increase in the near future.

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Results and Discussion

Although many crops have a long history of human selection, this has not, in most cases, circumvented their pollinator dependency. Pollinators can even enhance seed production of genetically engineered crops such as canola, soybean, and sunflower [14–16]. Interestingly, the incidence of pollination limitation (i.e., the percent of species that do not express their full reproductive potential in terms of fruit or seed set when pollination is limited) is relatively high among cultivated plants, ~60%, similar to the incidence observed in wild species [17, 18]. For these reasons, we expect that many crops could be susceptible to current declines in pollinator abundance and diversity of wild pollinators [1, 19, 20] and increasingly frequent collapses of managed honey bee (*Apis mellifera*) populations [2, 3, 21, 22].

Using FAO data [9], we examined temporal trends in yield, total production, and cultivation of crops over the past five decades in relation to pollinator dependency at a global scale. Particularly, we compared the group that depends to some extent on pollinators to produce the parts we consume (fruits or seeds) to the group of crops that does not depend on animal pollination, mostly because they are wind- or autogamously pollinated or cultivated for their vegetative parts (e.g., leaves, stems, tubers, etc.). This latter nondependent group also includes crops, such as potatoes and other vegetables, which do not depend directly on pollinators for the production of the parts we consume but for which pollinators are still important for propagation via seed or in breeding programs. The animal-pollinated crops represent a phylogenetically diverse group of species for which production, in terms of number or size of the seeds or fruits, is influenced by the presence of pollinators. The degree of dependence, however, varies greatly, such that absence of effective pollinators would reduce production by 100% in the extreme case, and by only a few percent for low-dependence species [5, 23]. Temporal trends were analyzed separately for the developed and developing world (see justification in the Supplemental Data available online).

The most stringent expectation from the hypothesis that global agriculture is experiencing a pollination shortage [6–8, 24] is that, all else being equal, pollinator-dependent crops should show declining average yield (i.e., metric tonnes per hectare) during at least the last part of the 45 year study period, a trend that would not be observed among the nondependent crops. This is probably a highly naive prediction considering that nothing has remained equal; agriculture is substantially more intensified today than half a century ago, and there has been increasing use of selectively bred or genetically modified high-yielding crop varieties [10]. We might then expect an increase over time in yield for most crops, regardless of their degree of pollinator dependency. However, under a pollination-shortage scenario we could predict a lower relative yield growth among pollinator-dependent than that among nondependent crops, a trend exacerbated in recent decades if pollinators had become an increasingly limiting resource [1].

Contrary to expectation, we found little evidence of differences in relative yield between pollinator dependent and nondependent crops. Yield has increased since 1961 by

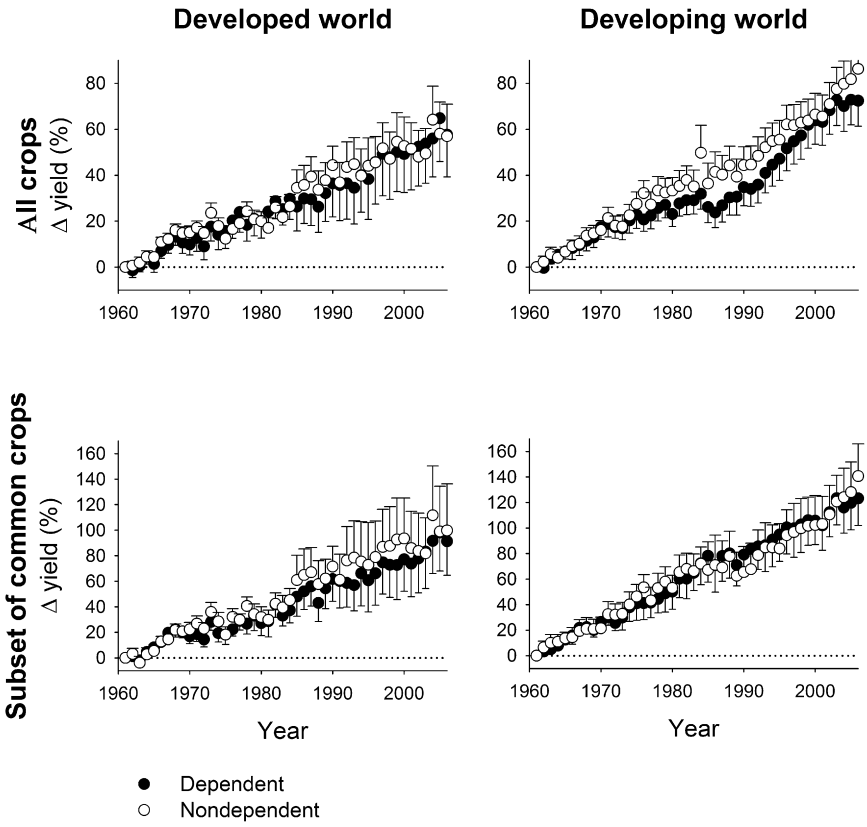

Figure 1. Temporal Trends in Mean Crop Yield from 1961 to 2006

For each crop grown in the developed world and developing word, we estimated the percent change of yield (Δ yield) at year *t* with respect to its value in 1961. The depicted means (±1 SE) in relative yield were estimated from all pollinator-dependent and nondependent crops included in our data set and from a subset of ten pollinator-dependent and ten nondependent crops widely cultivated in temperate and subtropical regions worldwide. For instance, this figure shows that the yield of commonly cultivated crops has doubled over the study's 45 year period.

(mean ± 1 SE) 1.30% ± 0.32%/year in the developed world and 1.61% ± 0.17%/year in the developing world. Overall the mean relative yield of pollinator-dependent crops showed a similar increase over time as the mean relative yield of the nondependent crops for both the developed and developing world (Figure 1). We found no significant differences in the average growth rate in relative yield between dependent and nondependent crops in the developed world (mean ± 1 SE = 1.31 ± 0.50 versus 1.28% ± 0.35%/year, t test, $t = 0.05$, Df = 68, p = 0.96) or developing world (mean ± 1 SE = 1.53 ± 0.24 versus 1.72% ± 0.23%/year, t test, $t = -0.59$, Df = 80, p = 0.59). Because many tropical, pollinator-dependent crops are exclusively or predominantly cultivated in the developing world (e.g., Brazil nut, cocoa beans, oil palm, etc.), we also compared trends in relative yield for a subset of ten common pollinator-dependent crops and ten common nondependent crops (see the Supplemental Data for details on crop selection). Analysis of this crop subset revealed no significant effect of pollinator dependency despite a trend toward a lower growth rate in average yield among pollinator-dependent than in that among nondependent crops in both the developed and developing world (Figure 1, Figure S1, and Table S1). Thus, these results do not support the view that a pollination shortage affects agriculture at a global scale.

Further distinction among dependent crops does suggest, however, that high pollinator dependence might impose a limit to the rate of yield growth. This was particularly apparent in the case of the highly pollinator-dependent crops from the developing world that exhibited an average growth rate in relative yield that was half the rate shown by the crops with low pollinator dependence (Figure S2 and Table S2). A similar pattern was found in the developed world once we excluded a crop complex, *Cucurbita* spp., a putative outlier in terms of its rapidly increasing annual growth rate in relative yield. These results imply that the availability of effective pollinators may be imposing an upper limit to many crops' yield increase that has not been completely offset by agricultural intensification, selective breeding, or genetic engineering. If growth in yield of highly pollinator-dependent crops is limited by pollinator availability, there will be an even greater demand for agricultural land to meet growing global consumption.

The subset of 20 shared crops also illustrates differences in yield according to the extent of development in the region. Despite the fact that productivity of both pollinator-dependent and nondependent crops increased almost 2-fold during the study 45 year period, the differences between the developed and developing world in absolute yield in 1961 (mean ± 1 SE = 5.8 ± 1.63 versus 3.3 ± 0.94 Mt/ha, paired t test, $t = 3.14$, Df = 19, p = 0.0053) still persisted in 2006 (mean ± 1 SE = 10.5 ± 2.88 versus 7.6 ± 2.51 Mt/ha, paired t test, $t = 2.75$, Df = 19, p = 0.012). Higher absolute crop yields observed in the developed world compared with the developing world presumably reflect disparate socioeconomic conditions and differences in agricultural intensification and subsidy policies [12, 13]. However, these contrasts, as well as environmental differences between these two regions of the world, did not seem to influence to any large extent differences in the growth rate in relative yield between pollinator-dependent and nondependent crops (Figure 1, Figure S1, and Table S1). The absence of a positive correlation in the annual growth rate in relative yield across this shared crop subset between the developed and developing world ($r = -0.135$, N = 20, p = 0.57), further implies that growth in yield is influenced quite idiosyncratically, to at least some extent, by socioeconomic or environmental factors rather than by intrinsic crop traits. Thus, although differences between the developed and developing world appear to be important drivers of change in agriculture, none of these changes is so strongly linked to the pollination problem that a clear signal emerges.

Unlike yield, aggregate production of pollinator-dependent and nondependent crops showed strikingly different temporal trends. In both the developed and developing world there has been a steady increase in the production of pollinator-dependent crops that surpassed the increase rate in the production of nondependent crops (Figure 2). Pollinator-dependent crops contributed 8.4% to total agriculture production in the

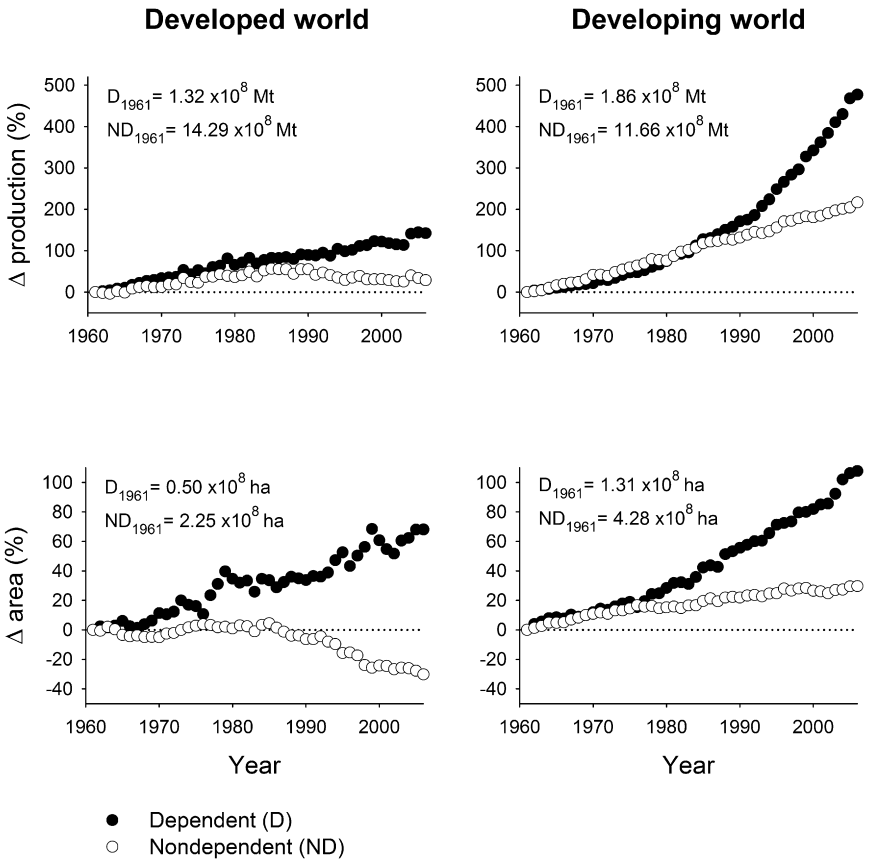

Figure 2. Temporal Trends in Total Crop Production and Cultivated Area from 1961 to 2006

Shown are the aggregate production and cultivated area of all pollinator-dependent and nondependent crops grown in the developed and developing world included in our data set relative to their respective 1961 values (i.e., Δ production and Δ area). For instance, the figure reveals that the area cultivated with pollinator-dependent crops has increased by nearly 70% for the developed world and ~100% for the developing world over the study's 45 year period. Absolute values for 1961 are provided for each variable.

developed world in 1961, whereas this value increased to 14.7% by 2006. Indeed, in the developed world the production of nondependent crops started to decline in the late 1980s; such a decline was related to a drop in cereal production in North America and Europe. This decline was driven by factors unrelated to crop breeding and pollination systems but related to changes in agricultural subsidies and the economic and political disruption created by the fall of communism in Eastern Europe and the former Soviet Union [25]. Similarly, although aggregate production of both dependent and nondependent crops showed a vigorous increase in the developing world, the relative increase in production of dependent crops appears to be exponential, contrasting with the linear growth shown by the nondependent crops (Figure 2). Therefore, pollinator-dependent crops contributed 13.7% to total agriculture production in the developing world in 1961, whereas this value increased to 22.6% by 2006. Our estimates for aggregate production of crops that depend at least partially on pollinators for the parts that we consume are below the recent estimate of 35% [5] because we did not include crops that depend on pollinators only for the seeds used for sowing or breeding rather than for the plant parts that we consume. Including all these crops in the dependent crop category would only accentuate the differences in the temporal trends we observed in total production and cultivated area according to the pollinator-dependency category. Thus, despite claims and evidence of strong declines in domestic and wild pollinators reported for different regions of the world [1, 3, 20], the aggregate production of pollinator-dependent crops has been steadily increasing over the last decades.

Changes over time in the relative contribution of pollinator-dependent and nondependent crops to global agriculture production were strongly associated with changes in the land area cultivated with these two crop types. We estimated that the global area occupied by agricultural crops expanded by ~23% from 1961 to 2006. The largest proportion of this increase can be attributed to the cultivation of pollinator-dependent crops, including several oil crops and a diversity of fruit trees and shrubs (Table S3). In the developed world, the land area cultivated with dependent crops increased nearly 70% between 1961 and 2006, whereas the area cultivated with nondependent crops stayed relatively constant until the late 1980s and declined by almost 40% since then (Figure 2). As a consequence, the percentage of cropping land devoted to pollinator-dependent crops in the developed world increased from 18.2% in 1961 to 34.9% in 2006. In the developing world, cultivation of both dependent and nondependent crops expanded over the time period considered, but the cultivation of dependent crops expanded at a higher rate than nondependent crops (Figure 2). Whereas dependent crops as a group occupied 23.4% of all cropping land in the developing world in 1961, this figure increased to 32.8% by 2006. The net effect of these trends is that global agriculture has become increasingly pollinator dependent over the last five decades. This increase in the relative representation of crops dependent on pollinators may in turn relate to increasing diversification in the human diet, particularly in industrialized nations, and globalization in food trade [26]. This trend might be further exacerbated in the future as some fast-expanding, insect-pollinated crops (e.g., oil palm and canola) are candidates for large-scale biofuel production [27].

Conclusions

A decline in domestic and wild pollinators brought about by local and global environmental degradation might be compromising the production of pollination-limited crops. Although we found some evidence that high pollinator dependence might be imposing a limit on the rate of yield growth, data we analyze here do not support the hypothesis that pollinator decline has affected crop yield at a global scale (see also [28]). This result does not contradict existing evidence of diminished fruit or seed set of crops grown in landscapes with little natural vegetation (e.g., [16, 29–31]), but it does suggest that these phenomena recorded at local scale do not aggregate up to a global depression in yield by pollinator-dependent crops.

On the other hand, our results reveal a "flowering-the-earth" trend; during the last 45 years there has been a net increase in the total area devoted to agriculture and a clear shift in the relative importance in the cultivation of pollinator-dependent versus nondependent crops at a global scale. Spread in the cultivation of these pollinator-dependent crops has occurred not only through the destruction and replacement of natural and seminatural habitats but also at the expense of land previously cultivated with pastures and nondependent crops [32, 33]. In any event, the global increases over time we report in the absolute and proportional area of cropping land devoted to cultivation of animal-pollinated crops may have important ecological and economic consequences in terms of growing pollination demands from declining domestic and wild pollinator stocks.

Supplemental data

Supplemental Data include Experimental Procedures, two figures, and three tables and can be found with this article online at http://www.current-biology.com/supplemental/S0960-9822(08)01240-2.

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