

Current Biology



Volume 19
Number 11

June 9, 2009

www.cellpress.com

**Increasing Demands on Global
Pollination Capacity**

The Global Stock of Domesticated Honey Bees Is Growing Slower Than Agricultural Demand for Pollination

Marcelo A. Aizen^{1,*} and Lawrence D. Harder²

¹Laboratorio Ecotono
INIBIOMA-CONICET and Centro Regional Bariloche
Universidad Nacional del Comahue
Quintral 1250
8400 Bariloche
Río Negro
Argentina

²Department of Biological Sciences
University of Calgary
Calgary, Alberta T2N 1N4
Canada

Summary

The prospect that a global pollination crisis currently threatens agricultural productivity has drawn intense recent interest among scientists, politicians, and the general public [1–5]. To date, evidence for a global crisis has been drawn from regional or local declines in pollinators themselves [6–9] or insufficient pollination for particular crops [9, 10]. In contrast, our analysis of Food and Agriculture Organization (FAO) [11] data reveals that the global population of managed honey-bee hives has increased ~45% during the last half century and suggests that economic globalization, rather than biological factors, drives both the dynamics of the global managed honey-bee population and increasing demands for agricultural pollination services [12]. Nevertheless, available data also reveal a much more rapid (>300%) increase in the fraction of agriculture that depends on animal pollination during the last half century, which may be stressing global pollination capacity. Although the primary cause of the accelerating increase of the pollinator dependence of commercial agriculture seems to be economic and political and not biological, the rapid expansion of cultivation of many pollinator-dependent crops has the potential to trigger future pollination problems for both these crops and native species in neighboring areas. Such environmental costs merit consideration during the development of agriculture and conservation policies.

Results and Discussion

Global Pollinator Decline?

Recent concerns of a global decline in pollinator abundance [2, 5, 13] have been raised by the accumulation of related regional evidence, including a drop in the number of domestic honey-bee colonies in the USA [14], a reduction in the abundance and diversity of wild bees in Europe [6], and a plethora of studies from around the world showing local decreases in pollinators due to habitat fragmentation [15] and agricultural intensification [9]. As a consequence, the implication that agricultural production may suffer from an intensifying pollination shortage has received much media attention, becoming an

issue of widespread interest and concern [14]. As a reflection of these concerns, the term “pollination crisis” was coined to highlight the potential effects of a global pollinator decline on the human food supply [1, 3]. Most recently, these concerns were voiced in Resolution T6-0579/2008 of the European Parliament, which stated “...whereas the beekeeping sector throughout the world, and more particularly in Europe, is encountering very serious difficulties...(and) only bees, in sufficient numbers, can guarantee pollination...it is essential to respond without delay to the crisis in bee health in an appropriate manner and with effective weapons” [16].

Regrettably, despite increasing claims of global pollinator declines [13], the data needed to assess global changes in the abundance and diversity of wild pollinators are not currently available. Instead, we analyze temporal trends in the total number of commercial hives of the domesticated honey bee, *Apis mellifera*, based on the database of the FAO of the United Nations [11]. The honey bee is managed for both honey production and pollination services [17] and is the single most important crop pollinator [18]. According to the FAO data, the global stock of commercial honey-bee colonies increased by ~45% since 1961 (Figure 1A, solid black line). The main exceptions to this global increase involve long-term declines in the USA and some European countries, but these are outweighed by rapid growth elsewhere (Figure S1 available online). Thus, despite variation among countries, the overall FAO data reveal that at least domesticated honey bees are not declining globally.

The long-term increase in the global number of hives was interrupted by a brief decline between 1991 and 1996, which may provide evidence of biological mechanisms that could precipitate a honey-bee decline. For example, this dip in hive numbers could have resulted from diseases caused by parasitic mites and other still unknown recent factors afflicting commercial honey-bee hives in the USA [8, 14], the country with the second-highest honey production at the beginning of the time series. However, the American population of honey-bee hives has declined relatively consistently since 1961 (average rate = –1.79% per year), so that exclusion of the USA data elevates the trend line for the remaining countries but has little impact on the slump in global hive numbers during the early 1990s (Figure 1A, blue line). Instead, this perturbation may partly reflect political change associated with the dissolution of the Soviet Union, given that it largely disappears when data for Soviet Bloc countries are excluded (Figure 1A, red line). Thus, the temporal decline in the global number of hives observed during the 1990s might have resulted from the political and economic disruption caused by the Soviet collapse, rather than from widespread ecological factors.

The increase in the global population of managed honey-bee hives during the past half-century could represent a compensatory response to an agricultural pollination crisis caused by declining service by nonmanaged pollinators, or it may simply reflect increased demand for honey. Increased global demand for crop pollination should have precipitated faster growth in the number of honey-bee hives than in honey production itself during recent decades. For example, in the USA and other countries, honey-bee hives are moved long distances primarily

*Correspondence: marcelo.aizen@crub.uncoma.edu.ar

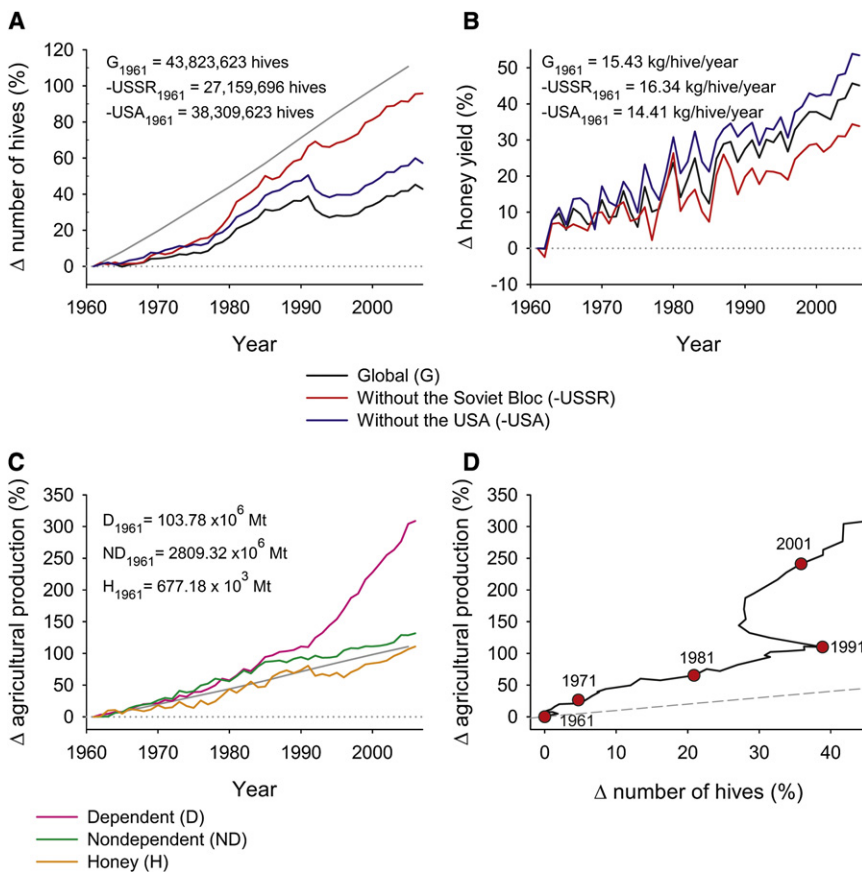


Figure 1. Changes in Global Numbers of Honey-Bee Hives, Agricultural Production, and Human Population between 1961 and 2007

(A–D) Change (Δ) for variable x from 1961 until year t is represented as a percentage of the value of x during 1961, x_{1961} , which is presented numerically for (A) number of hives, (B) honey yield, and (C) agricultural production. The figure demonstrates that the global number of commercial honey-bee hives, as reported by the Food and Agriculture Organization of the United Nations, has increased since 1961, despite a brief decline during the early 1990s mostly related to the dissolution of the Soviet Bloc (A). Notwithstanding this decline, efficiency in honey yield (i.e., annual production per hive) increased during the last five decades (B). Production of honey and the > 90% of agricultural production that is independent of animal pollination (C) increased at a rate similar to that of the global human population growth (gray line in [A] and [C]). However, the growth in the fraction of agricultural production that requires the service of animal pollinators increased disproportionately since 1991, after economic globalization and the implementation of market economies in the former Soviet Bloc and China (C). The growth in the fraction of agricultural production that depends on pollinators outpaced the growth of the global stock of domesticated honey bees (D), as indicated by the elevation of the trajectory above the dashed gray line representing equal growth rates. Any possible link between growth rates of pollinator-dependent agriculture production and abundance of managed honey bees decoupled abruptly in 1991.

to ensure pollination of valuable crops, such as almonds, rather than to harvest honey [17, 19]. In contrast, the FAO data reveal a strong positive, rather than negative, global trend in honey production per hive (Figure 1B, solid black line) and an overall increase in total honey production of > 100% since 1961 (Figure 1C, orange line), which is more than twice the average growth rate in the number of commercial honey-bee colonies during the same period (Figure 1A, solid black line). Furthermore, the increase in honey production during the last half-century closely tracks the increase in the human population during the same period (Figure 1C, compare gray and orange lines), which is consistent with honey production growing to satisfy a fixed global per capita demand for honey. Finally, although underreporting of domesticated honey bees devoted to crop pollination might unduly stress the importance of honey bees for honey production rather than pollination, honey bees maintained exclusively for pollination appear to represent a minor proportion of the global stock of domesticated honey bees (see Supplemental Data). Together, these observations suggest that, despite the dominant role of *A. mellifera* in crop pollination, at a global scale, honey bees are reared mainly to produce honey, so rising pollination needs likely played a limited role in stimulating the observed increase in the global stock of domesticated honey bees.

The FAO data also clarify that national or even regional declines in the health and/or size of the managed honey-bee population cannot substantiate claims of a global pollinator decline or an attendant pollination crisis. Instead, global claims require global data, which are largely lacking. Despite the dominant role of *Apis mellifera* as a crop pollinator, the FAO data sheds no light on the many other species of

pollinators, including feral honey bees. Furthermore, brief negative episodes cannot provide unequivocal evidence of either the rate of future changes or their causes, should they occur. For example, although the mysterious colony collapse disorder has recently had an impact on American honey bees [8], the half-century decline in their numbers may partly reflect decisions by honey producers to leave the industry in the face of competition from cheaper imported honey, given that the USA became increasingly reliant on imported honey beginning in the late 1960s (Figure S2). Indeed, the economics of honey production, including the global division of human labor that is a hallmark of economic globalization [20], likely influence the global dynamics of managed honey bees more than agricultural and biological requirements for pollination. For example, the recent resolution of the European Parliament includes the revealing phrases “...whereas the (beekeeping) sector suffers unfair competition from products originating in third countries and imported into the Community market... action should be taken to tackle unfair competition from apiculture products originating in third countries, which is partly the result of lower production costs, particularly as regards the price of sugar and labour” [16]. Regardless of the motivation, the contrast between common perception and the FAO data emphasizes that claims of a global pollination crisis must be based on scientific evidence collected at the appropriate spatial and temporal scale. Until relevant data become available and clear patterns emerge, any claim of a global pollinator decline and associated pollination crisis must be considered as a matter of debate, rather than as fact. This conclusion does not detract from real biological problems in the honey-bee populations of some countries

[7, 14]; however, it emphasizes that solutions to those problems must be motivated locally, rather than globally, and must acknowledge the dominant influence of economics in the pollination represented by every spoonful of honey.

Pollination Dependence of Agriculture

Despite the growth of the global population of managed honey-bee hives, evidence reveals that global demand for pollinator-dependent crops may stress agricultural and ecological capacity to provide pollination. Agricultural crops vary greatly in their requirements for animal pollination, from those for which animal pollination is irrelevant because they are self-pollinating or wind pollinated to those that depend strictly on animal pollination [10]. The FAO data also reveal that, during the past half-century, agricultural production that is independent of animal pollination, which represents the bulk of agricultural output, has doubled, roughly matching the increasing demand for staple foods imposed by growth in the human population (Figure 1C, compare green and gray lines; see also [21]). In contrast, the almost 4-fold rise in agricultural production that requires animal pollination (Figure 1C, purple line) indicates increasing per capita demand, and, indeed, this pollinator-dependent fraction increased as a percentage of total agricultural production from 3.6% in 1961 to 6.1% in 2006 (see also [12, 22]). Included in this fraction is most of the production of several insect-pollinated fruit and nut crops [10], both temperate (e.g., plums, raspberries, and cherries) and tropical (e.g., mangos, guavas, and Brazil and cashew nuts)—products that have become commonly available in supermarkets around the world. This disproportionate increase in global human consumption of high-value crops [23] accompanied both globalization in food trade and the adoption of market policies by most former Soviet Bloc countries and China [24]. Thus, we propose that human trade and economic policies, rather than need, have created demand for increased cultivation of pollinator-dependent crops and pollinator dependency of global agricultural production.

Can this increase be sustained, and, if so, at what environmental cost? The rapid increase in the fraction of pollinator-dependent agricultural production greatly exceeds that of the global stock of domesticated honey bees, especially since 1991 (Figure 1D). That this disparity has been sustained to date implies one of two alternatives: that existing commercial stocks of honey bees are sufficient to satisfy current crop pollination demands or that wild bees and feral honey bees are increasingly subsidizing commercial agriculture as more land is cleared for the production of pollinator-dependent crops. Much current evidence demonstrates that pollination by unmanaged bees contributes substantially to the production of many crops, particularly in areas of low to moderate agricultural intensification, which provides a mosaic of crops and adjacent remnants of natural and seminatural habitats that offer suitable nest sites [9, 10, 25]. However, the disproportionate increase of agricultural land demanded by the cultivation of many high-value, pollinator-dependent crops could jeopardize this unmanaged pollination service by hastening destruction of the remaining habitat and reducing habitat diversity [2, 5, 26]. Indeed, the ~25% expansion in cultivated area experienced by global agriculture during the last five decades involved mostly crops that depend on pollinators [12]. Furthermore, as we described above, available evidence indicates that honey bees are managed globally primarily for honey production, rather than pollination, so that relatively slow growth in hive numbers probably cannot satisfy

increased demand for agricultural pollination or mitigate any loss of native pollinators. Finally, honey bees are an invasive species in practically all areas where they are introduced [27], and they commonly steal pollen from native plant species without pollinating or while pollinating them inefficiently, reducing their seed production [28]. Thus, although the primary cause of the accelerating increase of the pollinator dependence of commercial agriculture is economic and political, rather than biological, the rapid expansion in the cultivation of many pollinator-dependent crops has the potential to trigger future pollination problems for both these crops and native species in adjacent areas. Such environmental costs warrant recognition and consideration during the development of agricultural and conservation policies.

Experimental Procedures

Data Set

The FAO of the United Nations has assembled detailed information on stocks of domestic honey bee (*Apis mellifera*), honey production, and crop cultivation for nearly five decades, based on data provided annually by member countries [11]. We accessed the FAO database to compile yearly data, from 1961 to 2007, on the number of honey-bee hives and honey production (in metric tonnes, Mt) for individual countries. We pooled data from the countries that comprised the former Soviet Union, Yugoslavia, and Czechoslovakia after their dissolution. We also pooled data from Belgium and Luxembourg after 1999 because they had previously reported data as one entity (i.e., Benelux). The FAO data set contains only one time series for Germany, so data for the former Federal German Republic and Democratic German Republic could not be distinguished. To avoid biases, we considered data only for countries with complete time series since 1961, which represented 99.6% of global honey-bee hives reported for 2005, but only 86.2% of the global figure for 2007, because India first reported data on honey-bee stocks in 2006. For honey production, we estimated production until 2006 because about 10% of the countries included in our global calculation had yet to report 2007 data. Our estimate of global honey production represents 99.3% of the global value reported by the FAO. We assessed the influences of the USA and the former Soviet Bloc (i.e., USSR, Bulgaria, Hungary, Poland, Romania, Czechoslovakia, and Germany), including the nonaligned Albania and Yugoslavia, on global trends in the number of honey-bee hives and efficiency (kg/hive) of honey production by alternatively removing their data.

We based our estimates of agricultural production on a data set used for previous studies [12, 22], which considered data from the FAO [11] concerning production estimates from 1961 through 2006 for 87 leading crops—52 represented by single species and 35 by groups of two or more often taxonomically related species. We summed data for the developed and developing world that had been analyzed separately in those previous studies. Together, the single and multispecies crops included in this study accounted for 82.8% of total global agricultural production during 2006. These crops were selected based on existing information about their pollinator dependence in the recent review of Klein et al. [10]. A crop was considered pollinator dependent if animal pollination is required to maximize the production of fruits or seeds consumed by humans, whereas it is nondependent if it is either pollinated abiotically (wind) or autogamously or cultivated for vegetative parts (e.g., leaves, stems, tubers, etc.). More specifically, Klein et al. defined five classes of pollinator dependence based on a thorough evaluation of the existing literature [10]: class 0, none (production unaffected by exclusion of animal pollinators); class 1, little (0%–10% production reduction); class 2, modest (10%–40% reduction); class 3, high (40%–90% reduction); and class 4, essential (>90% reduction without pollinators). Variation in pollination requirements among cultivars within single crops and among species in crop complexes precluded more refined categorization.

The trend in global human population growth was represented by semidecadal data for 1960 to 2005 from the Population Division of the United Nations [29]. To begin the time series in 1961, the first year of the agricultural series, we interpolated population size based on geometric growth between the values reported for 1960 and 1965.

Data Analysis

We partitioned total agricultural production into complementary components, the fraction that is independent of pollinators and the fraction that depends directly on pollinators. These fractions were estimated as

$\sum_i P_{it}(1 - d_i)$ and $\sum_i P_{it}d_i$, respectively, where P_{it} is the production (Mt) of crop i during year t and $0 \leq d_i \leq 1$ is its degree of pollinator dependency [22, 23]. We assumed that d_i was best represented by the midvalue of its respective category of pollinator dependency; hence, $d_i = 0, 0.05, 0.25, 0.65,$ or 0.95 for dependency classes 0, 1, 2, 3, or 4, respectively. A randomization procedure that assigned a pseudo-value of d_i drawn randomly from a uniform distribution bounded by the limits of a crop's respective pollination-dependence category revealed that uncertainty in the true dependency values of individual crops introduced an error of only $\sim 1\%$ in our estimations [22].

We used a common standardization procedure to compare temporal trends in honey-bee stocks and honey production, agriculture production, and human population. The percentage change of dependent variable x during year t compared to 1961 was calculated as $\Delta x_t = 100 \cdot (x_t - x_{1961}) / x_{1961}$. For instance, a value of $\Delta x_{2004} = 100\%$ for honey production represents a doubling of production between 1961 and 2004.

Supplemental Data

Supplemental Data include Supplemental Results and Discussion and two figures and can be found with this article online at [http://www.cell.com/current-biology/supplemental/S0960-9822\(09\)00982-8](http://www.cell.com/current-biology/supplemental/S0960-9822(09)00982-8).

Acknowledgments

The authors thank S.A. Cunningham, L.A. Garibaldi, L.K. Harder, P.D.E. Hensley, A.M. Klein, and two anonymous reviewers for useful comments and suggestions. Partial funding by the Argentina National Council for Research (PIP 5066) (M.A.A.), the National University of Comahue (B126/04) (M.A.A.), and the Natural Sciences and Engineering Research Council of Canada (L.D.H.) is acknowledged.

Received: January 17, 2009

Revised: March 6, 2009

Accepted: March 31, 2009

Published online: May 7, 2009

References

- Holden, C. (2006). Report warns of looming pollination crisis in North America. *Science* 314, 397.
- Kremen, C., and Ricketts, T. (2000). Global perspectives on pollination disruptions. *Conserv. Biol.* 14, 1226–1228.
- Westerkamp, C., and Gottsberger, G. (2002). The costly crop pollination crisis. In *Pollinating Bees - The Conservation Link between Agriculture and Nature*, P. Kevan and V. Imperatriz Fonseca, eds. (Brasilia: Ministry of Environment), pp. 51–56.
- Withgott, J. (1999). Pollination migrates to top of conservation agenda. *Bioscience* 49, 857–862.
- Kearns, C.A., Inouye, D.W., and Waser, N.M. (1998). Endangered mutualisms: The conservation of plant-pollinator interactions. *Annu. Rev. Ecol. Syst.* 29, 83–112.
- Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemuller, R., Edwards, M., Peeters, T., Schaffers, A.P., Potts, S.G., Kleukers, R., Thomas, C.D., et al. (2006). Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science* 313, 351–354.
- Gross, M. (2008). Bee gloom deepens. *Curr. Biol.* 18, 1073.
- Oldroyd, B.P. (2007). What's killing American honey bees? *PLoS Biol.* 5, e168.
- Ricketts, T.H., Regetz, J., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Bogdanski, A., Gemmill-Herren, B., Greenleaf, S.S., Klein, A.M., Mayfield, M.M., et al. (2008). Landscape effects on crop pollination services: Are there general patterns? *Ecol. Lett.* 11, 499–515.
- Klein, A.M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., and Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proc. Biol. Sci.* 274, 303–313.
- FAOSTAT. (2008). ProdSTAT Database. Food and Agriculture Organization of the United Nations. Available at <http://faostat.fao.org/site/526/default.aspx>. Version updated June 11, 2008. Last accessed in December 2008.
- Aizen, M.A., Garibaldi, L.A., Cunningham, S.A., and Klein, A.M. (2008). Long-term global trends in crop yield and production reveal no current pollination shortage but increasing pollinator dependency. *Curr. Biol.* 18, 1572–1575.
- Kluser, S., and Peduzzi, P. (2007). *Global Pollinator Decline: A Literature Review* (Geneva: UNEP/GRID).
- National Research Council. (2007). *Status of Pollinators in North America* (Washington, DC: National Academies Press).
- Winfree, R., Aguilar, R., Vázquez, D.P., LeBuhn, G., and Aizen, M.A. (2009). A meta-analysis of bees' responses to anthropogenic disturbance. *Ecology*, in press.
- European Parliament. (2008). Resolution T6-0579/2008. Available at <http://www.europarl.europa.eu/oeil/file.jsp?id=5695902¬iceType=null&language=en>.
- Morse, R.A., and Calderone, N.W. (2000). The value of honey bees as pollinators of US crops in 2000. *Bee Culture* 128, 1–15.
- McGregor, S.E. (1976). *Insect Pollination of Cultivated Crop Plants*, U.S.D.A. Handbook 496 (Washington: U.S. Department of Agriculture, Agricultural Research Service).
- Sumner, D.A., and Boriss, H. (2006). Bee-economics and the leap in pollination fees. *Agric. Res. Econ. Update* 9, 9–11.
- Held, D., McGrew, A., Goldblatt, D., and Perraton, J. (1999). Global transformations. *ReVision* 2, 7–14.
- Dyson, T. (1999). World food trends and prospects to 2025. *Proc. Natl. Acad. Sci. USA* 96, 5929–5936.
- Aizen, M.A., Garibaldi, L.A., Cunningham, S.A., and Klein, A.M. (2009). How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. *Ann. Bot. (Lond.)*, in press. Published online April 1, 2009. 10.1093/aob/mcp076.
- Gallai, N., Salles, J.M., Settele, J., and Vaissière, B.E. (2009). Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecol. Econ.* 68, 810–821.
- Pelto, G.H., and Pelto, P.J. (1983). Diet and delocalization: Dietary changes since 1750. *J. Interdiscip. Hist.* 14, 507–528.
- Kremen, C., Williams, N.M., Bugg, R.L., Fay, J.P., and Thorp, R.W. (2004). The area requirements of an ecosystem service: Crop pollination by native bee communities in California. *Ecol. Lett.* 7, 1109–1119.
- Allen-Wardell, G., Bernhardt, P., Bitner, R., Burquez, A., Buchmann, S., Cane, J., Cox, P.A., Dalton, V., Feinsinger, P., Ingram, M., et al. (1998). The potential consequences of pollinator declines on the conservation of biodiversity and stability of food crop yields. *Conserv. Biol.* 12, 8–17.
- Goulson, D. (2003). Effects of introduced bees on native ecosystems. *Annu. Rev. Ecol. Evol. Syst.* 34, 1–26.
- Hargreaves, A.L., Harder, L.D., and Johnson, S.D. (2009). Consumptive emasculation: The ecological and evolutionary consequences of pollen theft. *Biol. Rev.* 84, 259–276.
- United Nations. (2007). *World Population Prospects: The 2006 Revision Population Database*. Available at <http://esa.un.org/unpp/>. Version updated September 20, 2007. Last accessed in December 2008.