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Full Length Research Paper

Pollinator-dependent production of food nutrients by fruits and vegetables in China

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Pollinator-dependent production of food nutrients in China has not been evaluated previously. Using Food and Agriculture Organization (FAO) crop production data and United States Department of Agriculture (USDA) food composition data, we examined the nutritional values of 41 common fruits and vegetables to assess the contribution of animal pollination to human nutrition. Most of these crops rely on insect pollinators to set fruit or seed to some degree. Pollinator-dependent plants yielded more than 80% of the protein, fat, zinc, selenium, calcium, phosphorus, potassium, copper, vitamin B1 and vitamin B5, over 90% of the dietary fiber, vitamin B6 and vitamin C, almost the entire quantity of alpha-carotene and beta-tocopherol, and the full amount of beta-cryptoxanthin and lycopene. On average, pollinator-dependent crops accounted for approximately 80% of the food nutrients produced by the plants surveyed in this study, and 20% of all nutrient output was directly derived from insect pollination. Careful management of insect pollinator populations is therefore of vital importance to providing a nutritionally adequate diet for the people of China.

Key words: China, Food and Agriculture Organization (FAO), food nutrients, fruits, insect pollinators, vegetables.

INTRODUCTION

Flower-visiting insects perform a vital and increasingly threatened ecosystem service -pollination (Klein et al., 2007; Potts et al., 2010). A recent study put the global economic value of animal pollination in 2005 at € 153 billion, and estimated that the consumer surplus loss might be as high as €310 billion if pollinator populations worldwide all collapsed at once (Gallai et al., 2009). In China alone, insect pollination was assessed to be worth more than 52 billion US dollars per annum (An and Chen, 2011). Over the past half century, pollinator dependency of global agricultural production has increased significantly (Aizen et al., 2008), growing faster than the stock of the domesticated honey bee, *Apis mellifera* and *A. cerana* (Aizen and Harder, 2009). In Europe and the US, the expansion of pollinator-dependent crop cultivation has been accompanied by long-term declines in managed honey bee populations (vanEngelsdorp and Meixner, 2010), and wild pollinators have recently shown signs of distress (Biesmeijer et al., 2006; Goulson et al., 2008; Williams and Osborne, 2009), making agricultural production of these regions ever more vulnerable to disruptions in pollination services.

Many researchers have attempted to quantify the value of animal pollination. Most such studies are focused on monetary benefits, calculated as either the value of crop production directly derived from animal pollination (Losey and Vaughan, 2006; Gallai et al., 2009), or the cost of replacing existing pollinators with alternatives (Allsopp et al., 2008). These two approaches, respectively known as the production value method and the replacement value method, tend to produce highly divergent figures (two orders of magnitude) (Allsopp et al., 2008). Such bio-economic valuation studies are inherently incapable of

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providing consistent results, because currency values, labor costs and food prices change constantly. The production method also fails to consider possible mitigation efforts that may reduce the impact of a pollination crisis, and rests upon the faulty assumption that large-scale reduction in crop output does not trigger food price increases. A further weakness is that both methods ignore costs incurred by crop-producing farmers. In contrast to market prices, nutritional compositions of food crops are relatively stable and can be readily compared across different temporal and spatial scales, thus providing a viable biophysical alternative for valuing pollination services.

Staple crops are mostly self-pollinated, wind-pollinated, or vegetatively propagated (Tilman et al., 2002). Because the edible parts of these plants supply most of the energy in the human diet (Prescott-Allen and Prescott-Allen, 1990), basic food security is largely immune to the loss of pollinators (Ghazoul, 2005). However, grains and starch-rich vegetables generally have low concentrations of micronutrients (DellaPenna, 1999), and much of these micronutrients are lost during food processing (Poletti et al., 2004). More than two billion people suffer from nutritional deficiencies due to over-reliance on staple crops (Welch and Graham, 1999), underscoring the importance of animal pollinated plants in supplying humanity with micronutrients. Vegetables and fruits are globally the most prominent crop categories in value of animal pollination (Gallai et al., 2009). With an economic vulnerability ratio of 25.5% in 2008, China's production of vegetables and fruits is almost ten percentage points more reliant on pollinators than the world average (An and Chen, 2011). These crops are thus ideal subjects for nutritional valuation studies.

MATERIALS AND METHODS

Using Food and Agriculture Organization (FAO) data from 2006 to 2010 (http://faostat.fao.org), we calculated mean annual productions of 41 common fruits and vegetables in China. Five year means were used instead of the latest yearly production figures in order to smooth out annual variations in crop output. Vague crop types (for example, fruit fresh nes) were excluded from this analysis. Nutrient content and refuse fraction data were obtained from the United States Department of Agriculture (USDA) National Nutrient Database for Standard Reference (2009) (http://ndb.nal.usda.gov). 30 nutrients were analyzed, including protein, fat, dietary fiber, nine minerals, eleven fat-soluble vitamins, and seven water-soluble vitamins. We did not attempt a more detailed analysis due to lack of data. Carbohydrates were omitted because these were abundantly supplied by staple crops.

Pollinator dependency was categorized into six classes according to Klein et al. (2007): none (class 0; production is not affected by pollinators), little (class 1; absence of pollinators leads to 0 to 10% reduction in production), modest (class 2; 10 to 40% reduction in production occurs without pollination service), high (class 3; animal pollinators contribute to 40 to 90% of production), essential (class 4; production drops more than 90% when pollinators are not available), and unknown (class 5; insufficient data). A dependency value was assigned to each class according to Gallai et al. (2009): class 0 = 0, class 1 = 0.05, class 2 = 0.25, class 3 = 0.65, class 4 = 0.95. Class 5 was assigned a dependency value of zero to ensure a conservative estimation of insect pollinators' direct contribution to nutrient production.

The amount of each nutrient produced by pollinator-independent crops was calculated using the following equation:

$$NVi = \sum NCi \times Pi \times (1 - Ri)$$

The amount of each nutrient produced by pollinator-dependent crops was calculated using the following equation:

$$NVd = \sum NCd \times Pd \times (1 - Rd)$$

Pollinator-dependent production of each nutrient was composed of portions respectively attributed to insect pollination and self- or wind-pollination:

$$NVip = \sum NVd \times D$$

$$NVsw = \sum NVd \times (1 - D)$$

where, NV = nutrient output; NC = nutrient concentration; P = mean annual crop production; R = refuse fraction; D = pollinator dependency; i = pollinator-independent; d = pollinator-dependent; sw = self- or wind-pollination; ip = insect pollination.

RESULTS

We examined nutritional compositions of five class 0 (dates, grapes, mushrooms and truffles, green peas, and spinach), nine class 1 (green beans, green chilies and peppers, grapefruit, lemons and limes, oranges, papayas, persimmons, tangerines and tomatoes), four class 2 (coconuts, eggplants, figs, and strawberries), nine class 3 (apples, apricots, avocados, cherries, cucumbers and gherkins, mangoes et al, peaches and nectarines, pears, plums and sloes), three class 4 (pumpkins et al., watermelons, and other melons), and 11 class 5 (artichokes, asparagus, bananas, cabbages and other brassicas, carrots and turnips, cauliflower and broccoli, garlic, lettuce and chicory, dry onions, green onions, and pineapples) crops. Table 1 shows the mean annual production values of these crop classes in the 2006 to 2010 period.

The 36 pollinator-dependent crops dominated the production of most food nutrients, containing more than 80% of the protein, fat, zinc, selenium, calcium, phosphorus, potassium, copper, vitamin B1 and vitamin B5, over 90% of the dietary fiber, vitamin B6 and vitamin C, almost the entire quantity of alpha-carotene and beta-tocopherol, and the full amount of beta-cryptoxanthin and lycopene (Table 1, Figures 1 and 3). The five non-dependent crops nonetheless out-produced the dependent ones in vitamin K, lutein and zeaxanthin (Table 1, Figure 2). On average, pollinator-dependent crops accounted for 80.69 ± 2.79% of the food nutrients produced by the 41 vegetables and fruits, and 20.15 ± 2.39% of the nutrient output was directly derived from insect pollination (unweighted means).

Table 1. Mean annual production values of crops in different pollinator dependency categories of 2006 to 2010.

Crop	Pollinator dependency value	Pollinator dependency class	Mean annual production (million tons)
Dates, grapes, mushrooms and truffles, green peas, and spinach	0	0	36.28
Green beans, green chilies and peppers, grapefruit, lemons and limes, oranges, papayas, persimmons, tangerines and tomatoes	0.05	1	86.67
Coconuts, eggplants, figs, and strawberries	0.25	2	23.12
Apples, apricots, avocados, cherries, cucumbers and gherkins, mangoes et al, peaches and nectarines, pears, plums and sloes	0.65	3	102.20
Pumpkins watermelons, and other melons	0.95	4	81.79
Artichokes, asparagus, bananas, cabbages and other brassicas, carrots and turnips, cauliflower and broccoli, garlic, lettuce and chicory, dry onions, green onions, and pineapples	0	5	116.97

DISCUSSION

We assumed that pollinator dependency ratios were best represented by the mid-value of their respective categories, and nutritional compositions listed on the USDA database were applicable to crops cultivated in China. Both assumptions are unlikely to hold true in reality. Moreover, we did not consider regional or seasonal variations in the nutritional makeup of food plants. We also omitted vague and minor types of fruits and vegetables. The results of this study therefore should be regarded as merely rough baseline figures. Further efforts are required for a more accurate understanding of pollinator-dependent nutrient production by fruits and vegetables in China. Nevertheless, the USDA database is the most reliable and comprehensive source of food nutritional compositions publicly available, thus should suffice for a preliminary investigation.

Micronutrient production by food plants has recently been quantified on a global scale (Eilers et al., 2011). The results of that study show that pollinator-independent staple crops contain large amounts of the water-soluble B vitamins. Unfortunately, heavy losses (for example, 94% reduction in vitamin B6 concentration) of these nutrients occur when whole grains are refined into widely consumed final products such as white rice (Welch, 2002). Although processing-related nutrient loss can be rectified by fortifying refined starchy products with artificially introduced micronutrients, such options are not always available for people living in less developed regions. Vegetables and fruits are thus vital sources of the B vitamins, especially folic acid that is essential during pregnancy for preventing neural tube defects in infants (Poletti et al., 2004) (Table 2).

Vitamin A deficiency is extremely prevalent, affecting 254 million preschool children worldwide (Allen et al., 2006). As a result, half a million children suffer irreversible loss of eyesight per annum (DellaPenna, 1999). While many animal products are excellent sources of vitamin A (USDA), and vitamin A-fortification is viable for a wide range of foods, darkly colored vegetables and fruits rich in beta-carotene nonetheless are important for ensuring vitamin A adequacy in the human diet (Trumbo et al., 2001). Vitamin C, vitamin E and carotenoids are well-recognized antioxidants (Stahl et al., 1998); carotenoids are also widely known to have anti-cancer properties (Donaldson, 2004).

Insect pollinated vegetables and fruits are important for supplying dietary minerals as well. Iron deficiency afflicts more than 2 billion people globally, resulting in large numbers of preventable infectious disease and cognitive impairment cases (Welch and Graham, 1999; Allen et al., 2006). While crops are not always the most economical source of dietary iron (Drewnowski, 2010), iron from animal products is more environmentally damaging due to the extremely poor production efficiencies of farm animals (Eshel and Martin, 2006). Adequate calcium intakes are essential for the development of bones and teeth, and for reducing bone loss and osteoporotic fracture risk in elderly people (Heaney, 2000). Dairy products are excellent at providing calcium, but carry relatively high environmental costs (Weaver and Plawecki, 1994). Furthermore, minerals contained in animal products are often accompanied by large amounts of saturated fatty acids that are not nutritionally beneficial (Drewnowski, 2010).

A recent study shows that insect-pollinated crops, especially vegetables and fruits, are vital sources of

Table 2. Absolute and percentage nutritional outputs by pollinator-independent crops (NVi), self- or wind-pollinated fractions of pollinator-dependent crops (NVsw), and insect-pollinated fractions of pollinator-dependent crops (NVip).

Nutrient	**Pollinator-independent crop**		**Pollinator-dependent crop**			
	NVi (g)	**NVi (%)**	**NVsw (g)**	**NVsw (%)**	**NVip (g)**	**NVip (%)**
Macronutrients						
Protein	6.616E+11	15.61	2.873E+12	67.78	7.039E+11	16.61
Fat	8.662E+10	11.69	4.542E+11	61.27	2.005E+11	27.04
Dietary fiber	5.093E+11	8.48	4.107E+12	68.38	1.390E+12	23.14
Minerals						
Calcium	1.262E+10	14.13	6.547E+10	73.29	1.124E+10	12.58
Iron	3.856E+8	23.53	9.772E+8	59.64	2.757E+8	16.83
Magnesium	1.054E+10	21.37	2.766E+10	56.07	1.113E+10	22.56
Phosphorus	1.321E+10	12.84	7.048E+10	68.48	1.923E+10	18.68
Potassium	9.247E+10	13.28	4.347E+11	62.41	1.693E+11	24.31
Zinc	1.250E+8	16.20	4.970E+8	64.41	1.496E+8	19.39
Copper	3.560E+7	14.84	1.472E+8	61.35	5.710E+7	23.81
Manganese	1.468E+8	20.30	5.037E+8	69.68	7.246E+7	10.02
Selenium	5.656E+5	16.37	2.606E+6	75.44	2.828E+5	8.19
Vitamins						
Vitamin A						
Carotenoids	5.355E+7	25.80	1.131E+8	54.51	4.087E+7	19.69
Alpha-carotene	7.653E+5	0.25	2.772E+8	90.54	2.821E+7	9.21
Beta-carotene	6.421E+8	28.72	1.180E+9	52.80	4.131E+8	18.48
Beta-cryptoxanthin	0	0	7.840E+7	37.33	1.316E+8	62.67
Lycopene	0	0	9.609E+8	40.12	1.434E+9	59.88
Lutein, zeaxanthin	1.442E+9	73.45	4.210E+8	21.45	1.002E+8	5.10
Vitamin E						
Alpha-tocopherol	2.383E+8	22.91	5.902E+8	56.74	2.116E+8	20.35
Beta-tocopherol	4.137E+5	4.38	5.869E+6	62.07	3.173E+6	33.55
Gamma- tocopherol	5.312E+7	31.37	9.291E+7	54.86	2.331E+7	13.77
Delta- tocopherol	1.102E+6	29.99	2.279E+6	62.05	2.926E+5	7.96
Vitamin K	5.506E+7	53.54	4.182E+7	40.67	5.955E+6	5.79
Vitamin B						
Thiamin (B1)	2.518E+7	14.07	1.213E+8	67.81	3.242E+7	18.12
Riboflavin (B2)	4.467E+7	25.78	9.515E+7	54.92	3.344E+7	19.30
Niacin (B3)	3.159E+8	20.28	9.282E+8	59.59	3.136E+8	20.13
Pantothenic acid (B5)	7.447E+7	10.44	4.359E+8	61.12	2.028E+8	28.44
Vitamin B6	3.668E+7	7.91	3.739E+8	80.63	5.317E+7	11.46
Folate, total (B9)	2.466E+7	32.53	4.240E+7	55.94	8.740E+6	11.53
Vitamin C	4.753E+9	8.48	4.172E+10	74.47	9.548E+9	17.05

micronutrients, and insect pollination is directly responsible for a significant portion of total nutrient production (Eilers et al., 2011). The results of our study indicate that these also hold true for China. Our disruptions in pollinator populations thus have the potential to jeopardize nutrition security of the Chinese people. Mitigation measures such as dietary supplementation and food fortification cannot adequately compensate for failing nutrient production by crop plants. Many Chinese are not yet well-educated and affluent enough to regularly

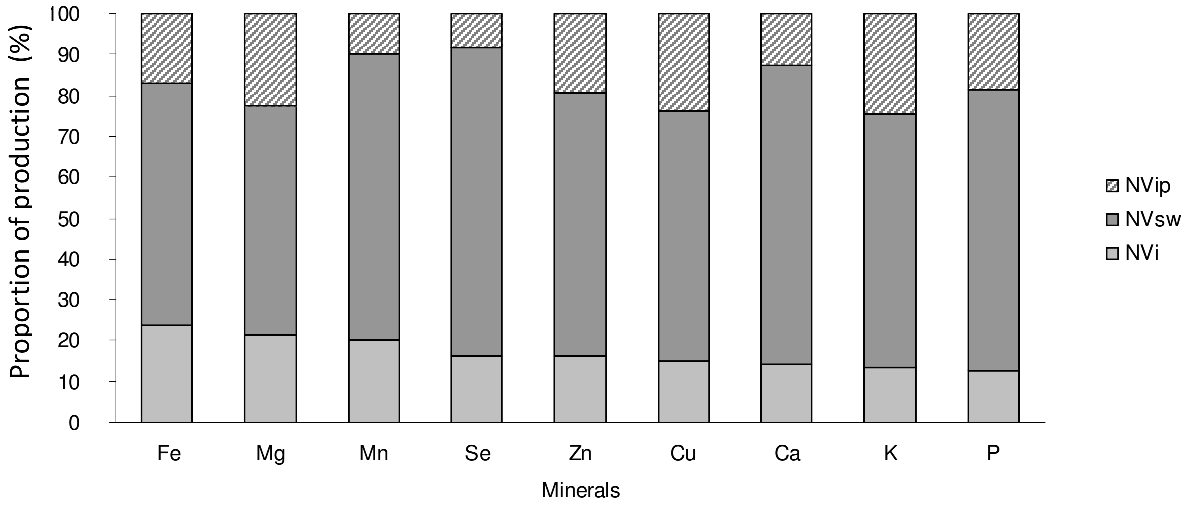

Figure 1. Percentage outputs of dietary minerals by pollinator-independent crops (NVi), self- or wind-pollinated fractions of pollinator-dependent crops (NVsw), and insect-pollinated fractions of pollinator-dependent crops (NVip). Fe = iron, Mg = magnesium, Mn = manganese, Se = selenium, Zn = zinc, Cu = copper, Ca = calcium, K = potassium, P = phosphorus.

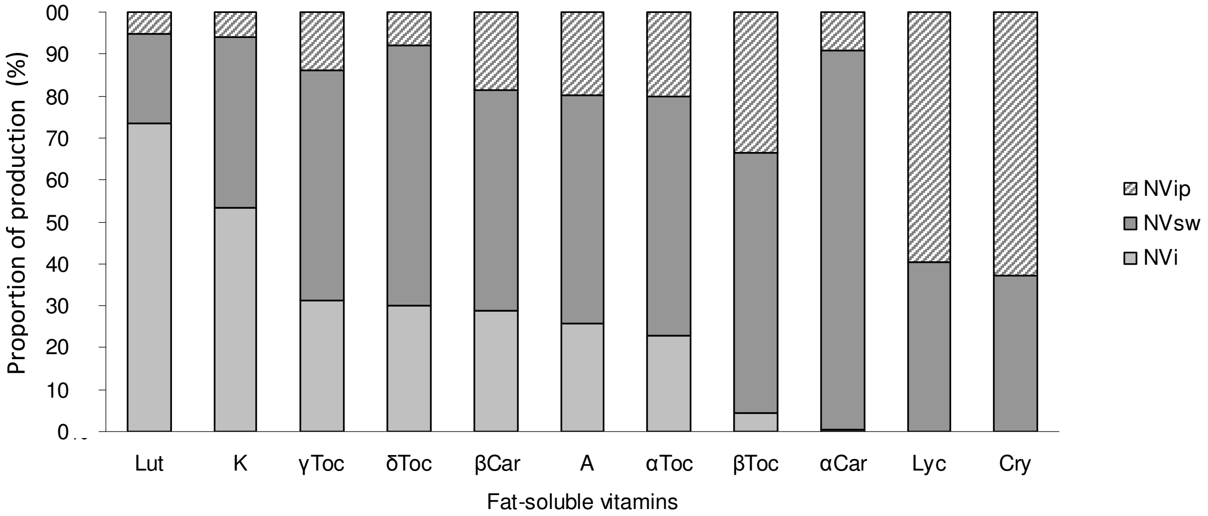

Figure 2. Percentage outputs of fat-soluble vitamins by pollinator-independent crops (NVi), self- or wind-pollinated fractions of pollinator-dependent crops (NVsw), and insect-pollinated fractions of pollinator-dependent crops (NVip). Lut = lutein and zeaxanthin; K = vitamin K; γToc = gamma-tocopherol; δToc = delta-tocopherol; βCar = beta-carotene; A = vitamin A; αToc = alpha-tocopherol; βToc = beta-tocopherol; αCar = alpha-carotene; Lyc = lycopene; Cry = beta-cryptoxanthin.

consume large amounts of dietary supplements such as herbal drugs and vitamin pills. Furthermore, because more than 87% of all angiosperms are pollinated by animals (Ollerton et al., 2011), it is very likely that the plants providing raw materials for supplements are themselves pollinator-dependent. Loss of pollination services thus will raise the cost of supplementation and fortification just when crop-derived micronutrients become less available. In addition, much is still unknown regarding the effects of many plant chemicals on human health. Some unidentified substances or combinations thereof, rather than the more familiar micronutrients analyzed in this study, may be the reason why fruits and vegetables are usually more beneficial to human health than dietary supplements. Biofortification (that is, genetically enhancing the ability of staple crops to produce micronutrients) is technically feasible (DellaPenna, 1999), but has encountered numerous difficulties (Poletti et al., 2004).

Fruits and vegetables are densely packed with

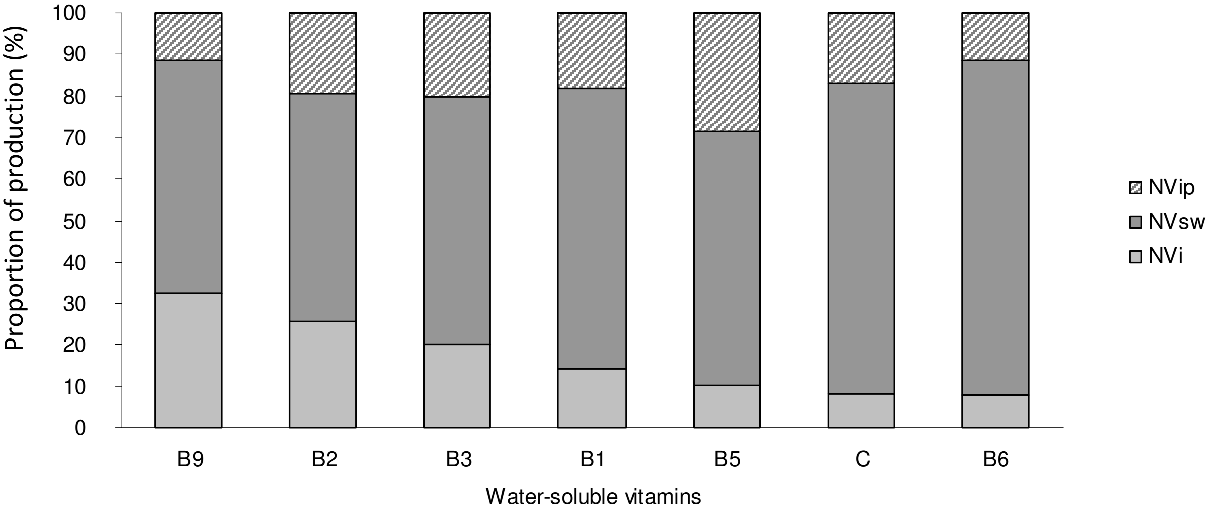

Figure 3. Percentage outputs of water-soluble vitamins by pollinator-independent crops (NVi), self- or wind-pollinated fractions of pollinator-dependent crops (NVsw), and insect-pollinated fractions of pollinator-dependent crops (NVip). B9 = total folate/folic acid; B2 = riboflavin; B3 = niacin; B1 = thiamin; B5 = pantothenic acid; C = vitamin C; B6 = vitamin B6.

micronutrients while containing limited amounts of energy and unwelcome substances (Drewnowski, 2010). As a result, these pollinator-dependent crops are crucial for maintaining the nutritional balance of the increasingly energy-rich Chinese diet. Meanwhile, pollinators are becoming ever more vulnerable to agricultural intensification, alien species, climate change, and the interactions of these ecological stressors (Potts eat al., 2010). Insect pollinator populations thus must be carefully managed to ensure a diverse and nutritionally adequate diet for the people of China. Given China's large population size and agricultural production volumes, what transpires in China can have significant ripple effects across the globe, the fate of China's insect pollinators is therefore of concern not only to the Chinese, but the entire humanity.

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