The Impacts of Yield on Nutritional Quality: Lessons from Organic Farming

Charles Benbrook¹

The Organic Center, 90063 Troy Road, Enterprise, OR 97828

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Abstract. A majority of well-designed studies comparing nutrient density (milligrams of a given nutrient per kilogram of food) in organically and conventionally produced fruits and vegetables show modest to moderately higher concentrations of most nutrients in organic produce. Likewise, organic produce is either as flavorful as or more flavorful than conventional produce and often tends to store better. Physiological factors that may account for these differences include the levels and form of nitrogen applied to crops, the balance of macro- and micronutrients in the soil, soil quality, average cell size, glycosylation status, and concentrations of plant secondary metabolites.

AN EASY QUESTION

Our colloquium poses the important question, “Crop yield and quality: can we maximize both?” For the majority of agronomic crops and ecosystems, the answer is “no,” at least if taste and nutrient density are central to one’s definition of food quality. By “nutrient density,” I mean the concentration of nutrients in a given food, which is typically reported as milligrams of nutrient per kilogram of food and may be measured and reported on a fresh or dry weight basis.

American agriculture has excelled in pushing the physiological limits of crops and farm animals through intensification of input use. Geneticists and breeders have consistently found ways to overcome constraints to higher yields and levels of animal production. However, these success stories sometimes have come at the expense of nutrient density (Benbrook et al., 2008; Davis et al., 2004; Mayer, 1997; White et al., 2005), organoleptic quality (Roth et al., 2005; Theuer, 2006), the environment (Kramer et al., 2006; Reganold et al., 2001), and in some cases plant and animal health and food safety (Baker et al., 2002; Benbrook, 2005c, 2005b, 2005d; Lu et al., 2006).

The risk of plant or animal health problems typically increases as yields or production per animal rises. Adverse impacts on the environment often increase in step with yields and production (Kramer et al., 2006; Reganold et al., 2001). For example, nitrogen use efficiency in corn systems typically declines as yields increase (Kahn et al., 2007); the health, reproductive performance, and longevity of dairy cows are clearly linked inversely to production levels (Oltencu and Algers, 2005). High yield production systems are often more vulnerable to pests. Farmers investing in high levels of input use tend to be more risk-averse in setting the pest population thresholds that trigger pesticide applications. For these reasons, pesticide use and impacts on nontarget organisms are often higher.

Much of the focus of agricultural research over the last few decades has been on pushing yields higher coupled with minimizing or otherwise dealing with the problems that arise when yields are pushed above one of these plateaus or thresholds. Although science and technology have been remarkably successful in pushing these plateaus higher, it has not eliminated them and likely never will for the vast majority of food. Accordingly, we cannot maximize both yields and crop quality when quality is defined in terms of nutrient density, taste, and food safety.

WHAT IS CROP QUALITY?

Most scientists agree that crop quality is a complex function of the nutrients in a food; the concentrations of those nutrients (i.e., nutrient density) and the forms in which they exist (particularly glycosylation status); freedom from pathogens, mycotoxins, chemical contaminants, and toxic levels of minerals or phytochemicals; and organoleptic quality (taste, flavor, aroma, appearance, mouth feel, storage stability). No one has a monopoly on how to measure quality nor the weight to place on various quality parameters.

We know that the nutritional quality of food for humans rests on several attributes and constituents in that food in addition to the traditional nutritional components measured (proteins, fats, carbohydrates, calories, and vitamin and mineral levels). In particular, an array of polyphenols, flavonoids, and antioxidants are clearly of great importance in promoting healthy growth and in preventing disease, including the neurological diseases of aging (Barbaste et al., 2002; Beecher 2003; Brandt et al., 2004; Galati et al., 2000; Grindler-Pedersen et al., 2003; Knekt et al., 1996; Mayer, 1997; Scalbert and Williamson, 2000; Wang et al., 2002). However, not just their levels in a particular food, but the form of the nutrients in food can dramatically impact bioavailability (Hounsborne et al., 2008). The mix and balance across nutrients ingested in a given day can alter the individual and combined impacts of nutrients on a person’s health (Brandt et al., 2004).

Moreover, the impact of nutrient forms on nutrient uptake can vary, sometimes significantly, by age, health status, gender, and human genetics. This is why the science

exploring the impacts of diet and food quality on human reproduction and development and disease prevalence is so inherently complex and prone to conflicting or confusing results.

The concentration of secondary metabolites in a given apple, tomato, or grain of wheat can be highly variable and is responsive to exogenous factors and interactions (Benbrook, 2005a). It is increasingly clear that soil quality, the forms and levels of applied nutrients, particularly nitrogen (N), and farming system choices impact yields, nutrient density, antioxidant levels, and taste in reasonably consistent ways (Benbrook et al., 2008; Mitchell et al., 2007). The literature contains many reports showing that individual flavonoid or antioxidant levels can rise or fall one- to threefold as a function of combination of genetics, soil quality, cropping systems, pest levels and pest management systems, and weather conditions (Benbrook, 2005a; Benbrook et al., 2008; Woese et al., 1997).

Although less frequently studied, the form of some nutrients in food also likely changes significantly as a function of these exogenous factors and farming system choices, in some cases exacerbating impacts on nutrient density and in other cases ameliorating them. For example, Yanez et al. (2008) showed that organic production can markedly alter both the glycosylation status and levels of chiral flavonoids in fruit juices, sometimes by severalfold. Much work lies ahead to sort out these interactions, what drives them, and how to channel them through farm management systems in ways that enhance food quality. Many scientists carrying out research on the impacts of organic farming systems on food quality are at or near the forefront of the quest for deeper understanding of these complex interactions.

WHAT DOES ORGANIC FARMING HAVE TO OFFER?

Two major factors account for the actual and potential benefits of organic farming in enhancing food nutrient density: acceptance of somewhat lower yield goals and improvements in soil quality that enhance plant and farm animal health.

The dominant path to higher yields on conventional farms over the last 50 years has

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¹To whom reprint requests should be addressed; e-mail cbenbrook@organic-center.org

been providing higher levels of nutrients to increasingly dense plantings. Halweil (2007) reviews the data showing correlations between yield levels, rising plant populations, and N application rates, especially in corn. Compared with most organic and lower-input conventional systems, the high-N path has resulted in fruits, vegetables, and grains that grow relatively fast, reach a larger size at maturity, and have lower levels of at least some nutrients (Benbrook et al., 2008). The quest for higher yields has involved genetic and management interventions to induce senescence and partition more nutrients to the setting of fruit and grain as opposed to vegetative growth.

In some cropping systems, one result of the successful pursuit of higher yields through high-N systems is fruit and vegetables with larger average cell sizes. The quality and flavor-conscious wine grape industry has, in particular, monitored the relationship among yield levels, fertilization, cell size, and crop nutrient (and flavor) density. Larger cells contain, on average, lower concentrations of secondary plant metabolites and cell walls that are more stretched and, as a result, more permeable and vulnerable to viruses (Benbrook et al., 2008). The nutrient and antioxidant dilution often observed in high-yield, high-N systems also tends to reduce the richness and intensity of flavors, because increases in sugar content overwhelm other, more subtle flavors (Theuer, 2006). Loss of flavor is generally exacerbated when fruit is picked before ripening.

The beneficial impact of long-term organic farming on soil quality deserves special emphasis in addressing crop yield-crop quality tradeoffs. Scientists studying the impacts of organic and conventional management on yields and crop quality in two long-term trials have recently stressed soil quality as a likely driver explaining the unexpectedly positive performance of organic systems. A team at the University of California–Davis has reported significant increases in flavonoid levels in organic tomatoes grown in a long-term cropping systems trial (Mitchell et al., 2007). They attributed this observation to the steady improvement of several soil quality indicators in the organically managed plots coupled with changes in the levels and form of N in the organic system. An Iowa State University team is reporting higher yields of organic corn and soybeans in another long-term trial (Larson, 2007). The University of California–Davis team found that the longer a field was managed organically, the larger the difference in flavonoid levels in organic versus conventional fruit.

There is tantalizing but inconclusive evidence in the literature that suggests that the yield threshold above which nutrient density declines can be increased by improving the balance and bioavailability of macro- and micronutrients in the soil (Mitchell et al., 2007). Too much readily available N, from any source, clearly tends to reduce nutrient density, flavor, plant health, and environmen-

tal impacts regardless of farming systems (Halweil, 2007). Whether soil quality enhancement in conventional or organic systems will consistently and reliably increase these thresholds is an open question.

Two additional factors play important roles and, in some crops and ecosystems, possibly dominant roles in enhancing food and crop quality under organic management: 1) pest levels and pest management systems; and 2) the diversity of above- and below-ground communities of organisms (Benbrook, 2005a). Polyphenol levels appear to be particularly sensitive to these factors in many fruit-cropping systems.

A growing body of research shows that organic farming increases the concentration of phenolics and antioxidants in food (Barbaste et al., 2002; Beecher, 2003; Benbrook, 2005a; Benbrook et al., 2008; Brandt et al., 2004; Galati et al., 2000; Herms, 1992; Knekt et al., 1996; Mitchell et al., 2007; Reganold et al., 2001; Wang et al., 2002; Woese et al., 1997). The Organic Center released a “State of Science Review” in Mar. 2008 comparing vitamin, mineral, protein, polyphenol, and antioxidant levels in 236 matched pairs of organic and conventionally grown foods (“matched” in terms of soil type, crop genetics, irrigation, harvest methods and timing, and weather). The report surveyed the experimental design and analytical methods in 97 published studies to identify “high-quality” and “acceptable” matched pairs of organic and conventional crops for assessment in terms of relative nutrient levels. On average, across 11 nutrients in 236 matched pairs, nutrient levels in organic food was 25% higher compared with the conventionally grown crops; differences up to 300% have been reported (Benbrook et al., 2008).

In summary, increasing yields through high-N farming systems typically comes at the expense of nutrient density, at least for some nutrients, and often flavor as well. With few exceptions and regardless of the farming system, it is not possible to simultaneously maximize both crop yields and crop quality, when crop quality is defined in terms of nutrient density, flavor, and food safety. However, the effort to do so is ongoing and vital, and important lessons will be learned from careful, rigorous comparisons of high N versus moderate N systems as well as comparisons of the food quality outcomes of organic and conventional farming systems.

Literature Cited

- Baker, B.P., C.M. Benbrook, E. Groth, III, and K.L. Benbrook. 2002. Pesticide residues in conventional, integrated pest management (IPM)-grown and organic foods: Insights from three US data sets. *Food Addit. Contam.* 19:427–446.
- Barbaste, M., B. Berke, M. Dumas, S. Soulet, J.C. Delaunay, C. Castagnino, V. Arnaudinaud, C. Cheze, and J. Vercauteren. 2002. Dietary antioxidants, peroxidation and cardiovascular risks. *J. Nutr. Health Aging* 6:209–223.
- Beecher, G.R. 2003. Overview of dietary flavonoids: Nomenclature, occurrence and intake. *J. Nutr.* 133:3248S–3254S.
- Benbrook, C. 2006. Chapter V: ‘Private sector initiatives to reduce children’s pesticide risks.’ In: *Successes and lost opportunities to reduce children’s exposure to pesticides since the mid-1990s*, Organic Center Critical Issue Report, Aug. 2006. <http://www.organic-center.org/science.pest.php?action=view&report_id=55>.
- Benbrook, C.M. 2005a. Elevating antioxidant levels in food through organic farming and food processing. The Organic Center. June 2007. <http://www.organic-center.org/science.antiox.php?action=view&report_id=3>.
- Benbrook, C. 2005b. Breaking the mold—Impacts of organic and conventional farming systems on mycotoxins in food and livestock feed. State of Science Review, The Organic Center. June 2007. <http://www.organic-center.org/science.safety.php?action=view&report_id=2>.
- Benbrook, C. 2005c. Tracking the impacts of the FQPA on pesticide dietary risks—A preliminary assessment. Consultant Report to the EPA Office of Inspector General.
- Benbrook, C. 2005d. Minimizing pesticide dietary exposure through the consumption of organic food. State of Science Review, The Organic Center. June 2007. <http://www.organic-center.org/science.pest.php?action=view&report_id=19>.
- Benbrook, C., X. Zhao, J. Yanez, N. Davies, and P. Andrews. 2008. New evidence confirms the nutritional superiority of plant-based organic foods. State of Science Review, The Organic Center. June 2007. <http://www.organic-center.org/science.nutri.php?action=view&report_id=126>.
- Brandt, K., L.P. Christensen, J. Hansen-Moller, S.L. Hansen, J. Haraldsdottir, L. Jespersen, S. Purup, A. Kharazmi, V. Barkhot, H. Frokiaer, and M. Kobaek-Larsen. 2004. Health promoting compounds in vegetables and fruits: A systematic approach for identifying plan components with impact on human health. *Trends Food Sci. Technol.* 15:384–393.
- Davis, D.R., M.D. Epp, and H.D. Riordan. 2004. Changes in USDA food composition data for 43 garden crops, 1950 to 1999. *J. Amer. Coll. Nutr.* 23:669–682.
- Galati, G., S. Teng, M.Y. Moridani, T.S. Chan, and P.J. O’Brien. 2000. Cancer chemoprevention and apoptosis mechanisms induced by dietary polyphenolics. *Drug Metabol. Drug Interact.* 17:311–349.
- Grinder-Pedersen, L., S.E. Rasmussen, S. Bugel, L.V. Jorgensen, L.O. Dragsted, V. Gundersen, and B. Sandstrom. 2003. Effect of diets based on foods from conventional versus organic production on intake and excretion of flavonoids and markers of antioxidative defense in humans. *J. Agr. Food Chem.* 51:5671–5676.
- Halweil, B. 2007. Still no free lunch: Nutrient levels in U.S. food supply eroded by pursuit of high yields. Critical Issue Report, The Organic Center. June 2007. <http://www.organic-center.org/science.nutri.php?action=view&report_id=115>.
- Herms, D.A. 1992. The dilemma of plants: To grow or defend. *Q. Rev. Biol.* 67:283–335.
- Hounsborne, N., B. Hounsborne, D. Tomos, and G. Edwards-Jones. 2008. Plant metabolites and nutritional quality of vegetables. *J. Food Sci.* 73:R48–R65.
- Kahn, S.A., R.L. Mulvaney, T.R. Ellsworth, and C.W. Boast. 2007. The myth of nitrogen fertilization for soil carbon sequestration. *J. Environ. Qual.* 36:1821–1832.
- Knekt, P., R. Jarvinen, A. Reunanen, and J. Maatela. 1996. Flavonoid intake and coronary mortality in Finland: A cohort study. *BMJ* 312:478–481.

- Kramer, S.B., J.P. Reganold, J.D. Glover, B.J. Bohannon, and H.A. Mooney. 2006. Reduced nitrate leaching and enhanced denitrifier activity and efficiency in organically fertilized soils. *Proc. Natl. Acad. Sci. USA* 103:4522–4527.
- Larson, A. 2007. Yields increase, soil resilience soars; Long-term research proves organic promise. Leopold Letter, Leopold Center for Sustainable Agriculture. Iowa State University.
- Lu, C., K. Toepel, R. Irish, R.A. Fenske, D.B. Barr, and R. Bravo. 2006. Organic diets significantly lower children's dietary exposure to organophosphorus pesticides. *Environ. Health Perspect.* 114:260–263.
- Mayer, A.M. 1997. Historical changes in the mineral content of fruits and vegetables. *Brit. Food J.* 99:207–211.
- Mitchell, A.E., Y.J. Hong, E. Koh, D.M. Barrett, D.E. Bryant, R.F. Denison, and S. Kaffka. 2007. Ten-year comparison of the influence of organic and conventional crop management practices on the content of flavonoids in tomatoes. *J. Agr. Food Chem.* 55:6154–6159.
- Oltenacu, P.A. and B. Algers. 2005. Selection for increased production and the welfare of dairy cows: Are new breeding goals needed? *Ambio* 34:311–315.
- Reganold, J.P., J.D. Glover, P.K. Andrews, and H.R. Hinman. 2001. Sustainability of three apple production systems. *Nature* 410:926–930.
- Roth, E., A.Z. Berna, K. Beullens, A. Schenk, J. Lammertyn, and B. Nicolai. 2005. Comparison of taste and aroma of integrated and organic apple fruit. *Commun. Agr. Appl. Biol. Sci.* 70:225–229.
- Scalbert, A. and G. Williamson. 2000. Dietary intake and bioavailability of polyphenols. *J. Nutr.* 130(Suppl):2073S–2085S.
- Theuer, R. 2006. Do organic fruits and vegetables taste better than conventional fruits and vegetables? *State of Science Review, The Organic Center*. June 2007. <http://www.organic-center.org/science.nutri.php?action=view&report_id=78>.
- Wang, S.Y., W. Zheng, and G.J. Galletta. 2002. Cultural system affects fruit quality and antioxidant capacity in strawberries. *J. Agr. Food Chem.* 50:6534–6542.
- White, P.J. and M.R. Broadley. 2005. Historical variation in the mineral composition of edible horticultural products. *J. Hort. Sci. Biotechnol.* 80:660–667.
- Woese, K., D. Lange, C. Boess, and K.W. Bogl. 1997. A comparison of organically and conventionally grown foods—Results of a review of the relevant literature. *J. Sci. Food Agr.* 74:281–293.
- Yanez, J.A., C.M. Remsberg, N.D. Miranda, K.R. Vega-Villa, P.K. Andrews, and N.M. Davies. 2008. Pharmacokinetics of selected chiral flavonoids: Hesperetin, naringenin, and eriodictyol in rats and their content in fruit juices. *Biopharm. Drug Dispos.* 29:63–82.