SOIL FERTILITY FOR FUNCTIONAL FOODS

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Introduction

In the agri-food industry today, two trends cannot be ignored. First, the health conscious "baby boom" generation is demanding and will continue to demand foods that enhance their wellness. Crop producers must increasingly focus on the goal of producing crops that meet their needs. Second, the tools of molecular biology give agricultural scientists the opportunity to attain that goal. Biotechnology involves not only genetic engineering, but also includes tools that enhance the traditional selection for desired traits, as well as the science to determine the health benefits of specific phytochemicals beyond carbohydrates, proteins, fats and vitamins. We as agronomists, soil fertility specialists and crop advisers must keep abreast of the newly evolving information in the fields of human and animal nutrition.

Functional Foods that Enhance Wellness

"Functional Foods" are defined as foods that contain bio-active ingredients thought to enhance health and fitness. They are also called "designer foods" or "pharma-foods". The active ingredients are phytochemicals, such as lycopene in tomatoes (see Table 1 for more examples). These phytochemicals are not among the traditional nutrients (carbohydrates, proteins, fats, minerals, and vitamins) and are often called "nutraceuticals", although that term is increasingly being used specifically for extracted concentrates (Zeisel, 1999). The therapeutic value of the active ingredients may differ depending on whether taken as supplement or consumed in whole food.

Functional foods are associated with the prevention and treatment of at least four of the leading causes of death: cancer, diabetes, hypertension and heart disease (Hasler, 1998). In addition, some help with other medical ailments including neural tube defects, osteoporosis, abnormal bowel function and arthritis. Their modes of action are diverse (Table 2).

The functional food industry is considered to have tremendous potential for market growth. In 1997, the US food industry sales totaled $447 billion (B) with a growth rate of 3 to 5 percent per year. Of that total, about $80B could be considered "health food" (low-fat, low-calorie, etc.) and somewhere between $6B and $28B worth of functional foods and supplements were sold (Best, 1997; Hasler, 1998; PPI, 1999; Zeisel, 1999). The growth rate of the latter is estimated at 7 to 10 percent per year. The sales volume of "functional foods" can be considered similar to that of organic foods, but their prospects for future growth are better, owing to a more scientifically defensible rationale for their consumption (assuming that medical and nutritional research can sort out the many claims of various functional food ingredients). The potential future market in North America has been estimated at $250B. In Japan, functional foods are better defined and are regulated as "Foods for Specified Health Use" (FOSHU). About 80 products are already registered as FOSHU, and their sales are currently at $1.2B per annum. Some project a potential market of $200B by the year 2005.

Molecular Biology and Genetic Engineering

Exciting advances in gene transfer between species have led to speculation that "pharming", the production of extremely high-value medicines in crop plants, would present huge profit opportunities to crop producers. However, for many of the specialty pharmaceuticals that may be produced by plants, feed and food crops will not be candidates. Owing to the risk of contamination of the food supply, most of the pharmaceuticals will be produced in non-food crops like tobacco, andthe acreage requirements will be extremely modest. Because of concern over gene transfer, this type of production will be highly controlled and highly specialized, offering opportunities to very few producers.

In contrast, food and feed crops that are enhanced in nutritional or nutraceutical content offer opportunity to almost every crop producer. While most of the attention is paid to food crops, the benefits to animal production are equally valid. "Vetraceutical" is already a common term in small animal practice. One study at Iowa State University has shown a role for isoflavones in enhancement of swine carcass muscle percentage (Cook and Thompson, 1998). Thus, the discoveries in this new area of science that spans the gap between nutrition and medicine have potential to impact the definition of quality in both animal and human nutrition.

Public concern regarding genetic engineering has risen and will continue to grow. The issues associated with interspecific gene transfer are not limited to health and environmental safety, but also encompass deep moral and ethical issues which will take decades to resolve into some form of societal consensus. Thus, transgenics have an uncertain, albeit large, potential to impact crop production. However, molecular biology has also given plant breeders new tools to exploit existing within-species genetic material. Molecular DNA markers (RFLP, RAPD, AFLP) are highly applicable to the selection for increased levels of phytochemicals, nutraceutical substances and trace element bioavailability (Schachtman and Barker, 1999). Thus we can expect that breeders will quickly make progress in enhancing the nutraceutical components of the crop species in which they naturally occur.

Opportunities for Agronomy

Production of crops containing enhanced levels of functional food components will not be accomplished by genetics alone. Both weather and agronomic practices will have an impact, and plant nutrition certainly cannot be ignored. Plant metabolism of secondary phytochemicals is anabolic and energy-consuming. Thus, one might expect that well nourished plants would be more capable of producing phytochemicals. One example is the role of potassium (K) in enhancing the lycopene content of tomatoes by as much as 67 percent (Trudel and Ozbun, 1971). Phosphorus (P) is involved as an energy carrier in all plant metabolism. More specifically, the pentose phosphate pathway, unique to plants, has been linked to the production of anthocyanins (Gianfagna and Berkowitz, 1986). However, some phytochemicals are produced in response to stress conditions and might actually be enhanced under nutrient deprivation or adverse weather conditions. Finding the nature of these plant responses is an important agronomic research priority. Levels of fertility considered optimal for yield could be either suboptimal or excessive for optimum nutraceutical content.

How will the exciting changes in the food retail market impact the agronomy of corn, wheat and soybeans? The opportunities do not need to be limited to identity-preserved contract production. Indeed, many quality traits are impacted by weather. Therefore, growers will seek management options that maximize chances of, but do not necessarily assure, meeting standards for the quality components of interest. We can expect that the future quality standards for many commodity crops will be influenced by new knowledge of nutraceuticals and will become more complex than simple measures of test weight, crude protein, etc. There will also be premiums for those who can meet those standards.

Soybean Isoflavones: one example

Isoflavones are one of the most important phytochemicals in soybeans, and are thought to be responsible for the reduced rates of cancer, heart disease, and osteoporosis observed in people consuming soybeans. The Potash & Phosphate Institute has supported research to determine the effect of K fertility on soybean isoflavones. Soybeans grown at various levels of fertility in several 1998 field trials (see Table 3 for site descriptions) were analyzed for total isoflavone content.

At two of six sites, there was a significant positive relationship between K and isoflavone concentrations in the harvested soybeans (Figure 1). At the Paris, Ontario site, the response to applied K was clear (Table 4). There was also substantial variability among sites and varieties, but since each variety was grown at a separate site, the effect of location cannot be separated from the effect of variety. The data indicate that isoflavones are controlled by a number of factors, and K could be one of considerable importance. The specific involvement of K in isoflavone synthesis is unknown, other than as an enzyme cofactor as it is for many metabolic reactions. It is possible that the reason for the observed effect of K was its effect in stimulating plant growth, as yields at Paris were enhanced by applied K (Table 4).

Across these sites, there was also a strong relationship between yield and isoflavone concentration (Figure 2). This significant and positive association with yield is very encouraging, as it suggests that high yield is compatible with quality from a functional food perspective. Indeed, further research in this area may supply powerful information to convince consumers that modern high-yield agriculture produces quality food, rather than the "empty calories" many perceive.

Phytate and Trace Elements

The attention paid to the role of phytochemicals in health has also revealed new aspects of food components previously considered "anti-nutritional". While phytate is known to reduce absorption of calcium (Ca), zinc (Zn) and iron (Fe) in the human diet, and to limit P availability in the non-ruminant animal, it surprisingly has been shown to have a positive role in reducing the risk of prostate cancer in men. For some human populations, dietary phytic acid may have a positive role as an anti-oxidant and anti-colon cancer agent (Raboy, USDA-ARS press release).

Within seeds of all plants, phytate is the storage form of not only P, Ca and magnesium (Mg), but also for important trace elements such as Fe and Zn. In fact, phytate can enhance Zn uptake in plants by providing a sink for it – this may explain why phosphorus fertilization often increases the concentrations of trace elements [Zn, Fe, copper (Cu), manganese (Mn)] in whole grains (Rengel et al., 1999). Phytic acid forms insoluble precipitates with many trace metal ions (e.g. Zn^{2+} and Fe^{3+}) at the basic pH in the small intestine. While phytic acid inhibits Fe and Zn bioavailability to humans and animals, the naturally occurring form, phytin, may actually increase Fe bioavailability under some circumstances (Welch, 1997). Thus, the low-phytate strains of wheat, rice, and corn under development may have substantially altered food quality from a trace element point of view. The seedling vigor of low-phytate genotypes of corn in low-P soils has also been shown to be markedly reduced, even after addition of fertilizer P (R.M. Welch, pers. comm.).

Genetic engineering is producing several other innovations with respect to P. One is the use of fungal cultures to produce phytase enzymes to add to feed. Yet another, announced last summer at the University of Guelph, involved the linking of a mouse gene for synthesis of salivary protein to a phytase gene from *Escherichia coli* strain K12, transferring this DNA into fertilized pig embryos to be expressed in their salivary glands. The technology has been named "EnviroPig^{TM}". Heritability has yet to be proved, and regulatory approval for a genetically engineered pig is likely to take many years, but there is substantial potential for such animals to perform well on a lower P diet. The EnviroPig^{TM} is also one of the first products of genetic engineering financed by farmers – Ontario Pork has the exclusive license for its distribution, while the University of Guelph owns the patent. The size of investment required for breakthroughs in genetic engineering appears to be declining; thus, we can expect to see many more innovations appearing in the future.

Phytate is important because of its interactions with trace elements. Deficiencies of trace minerals [Fe, Zn, iodine (I) and selenium (Se)] and vitamin A currently affect more than two billion people worldwide (Welch and Graham, 1999). Enhancing "functional foods" is not only a market opportunity, it meets real human needs.

Summary

Research on the role of soil fertility has much to discover: not only about its impacts on crop yield, but also about a myriad of crop phytochemicals and nutritive minerals. Evolving trends in biotechnology and nutritional and health sciences have large implications for agronomy and agronomic research. Soil fertility specialists must pay particular attention to developments that enhance mineral uptake in plants and mineral bioavailability in crop products. The opportunity exists to produce crops of greater health benefit and, thus, of greater value. Part of this value can be translated into profit for the crop input and services supplier. The challenges are to sort the genuine health benefits from among many claims and to communicate the information to the consumer.

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Table 1. Examples of functional foods and their active phytochemical ingredients.

Functional Food	Nutraceutical Ingredients
Broccoli, cabbage, cauliflower	sulphoraphanes, indoles, carotenoids
Cranberries	quinic acid
Fish	omega-3 fatty acids
Flax	lignans
Garlic	allicin, flavonoids, organosulfur compounds
Ginseng	more than 30 ginsenosides
Oats	beta-glucan
Red grapes, red wine	resveratrol, quercitin, anthocyanidins
Soybean	isoflavones, lignans, saponins
Tomato	lycopene, carotenoids
Whole grains (oats, wheat, barley)	saponins, terpenoids, phytic acid

Table 2. Modes of action of functional food ingredients.

Mode of Action	Examples
Antibacterial substances	quinic acid in cranberry juice
Anticarcinogens	indoles, phenols, flavones, isoflavones, allyl sulfur compounds, sulphoraphanes
Antihypertensives	green and black tea polyphenols
Antioxidants	vitamins A, C, E; glutathione, polyphenols, flavonoids, isoflavones, lycopene
Food components with diminished allergenicity	*Lactobacillus* strain GG
Gastrointestinal function	beta-glucans in oats
Hypocholesterol agents	green and black tea polyphenols, soy foods, phytosterols
Immunomodulators	vitamin E
Phytoestrogens	isoflavones, extracts of rosemary and garlic
Probiotics (alter gastrointestinal and/or colonic microflora)	*Lactobacillus acidophilus*, *Bifidobacterium bifidum*
Substances that improve the bioavailability of minerals	fructooligosaccharides

Table 3. Characteristics of the six Ontario field sites.

Location	Variety	Soil Texture	Soil P	Soil K	Variables
Kirkton	First Line 2801R	silt loam	medium	medium	K, row width
Paris	OAC Bayfield	sandy loam	medium	low	K, row width
Melbourne	Westag 97	sandy loam	very high	medium	lime, P&K
Thamesville	Westag 97	sandy loam	very high	medium	lime, P&K
Woodslee	Westag 97	clay	medium	medium	lime, P&K
Rodney	S18-11	sandy loam	high	very high	K sources

Table 4. Effect of band-applied potassium (K) fertilizer on soybean yield and isoflavone content in a production field at Paris, Ontario in 1998. Leaf and seed K and isoflavone concentrations differed significantly ($p<0.002$).

K_2O Rate, lb/A	Leaf K, %	Seed K, %	Yield, bu/A	Isoflavones, ppm
90	2.1	1.7	37	2100
0	1.6	1.4	32	1740

*ppm = parts per million by weight

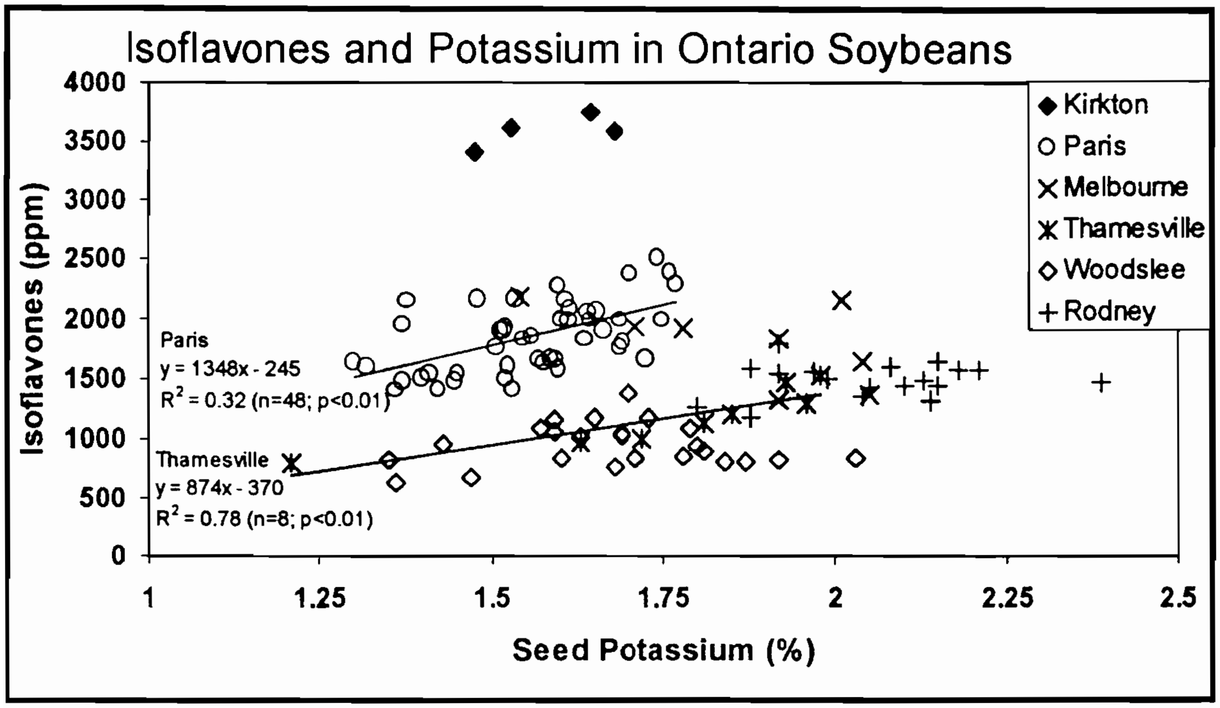

Figure 1. Isoflavone levels in soybeans from six Ontario sites in relation to soybean K content at harvest.

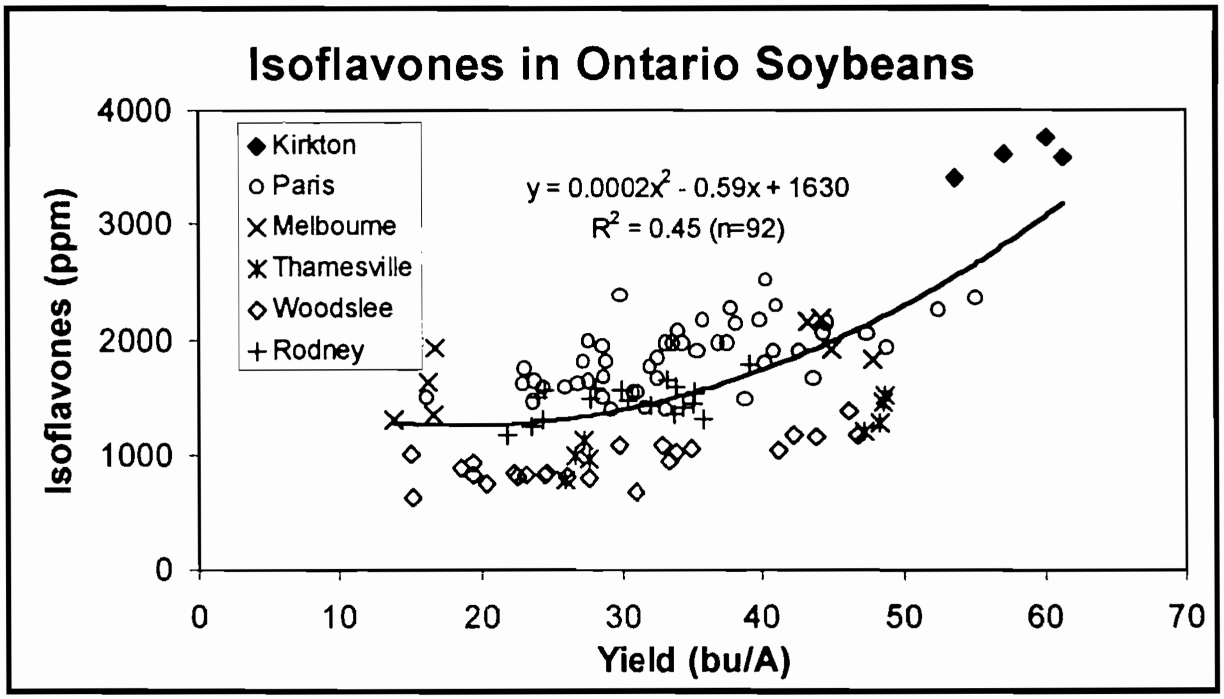

Figure 2. Isoflavone levels in relation to soybean yield.

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