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# *Ex Ante* Economic Impact Analysis of Novel Traits in Canola

**Anwar Naseem and Rohit Singla**

This study evaluates the potential economic impacts of ten novel traits in canola by employing a stochastic economic surplus model. Nitrogen use efficiency, water use efficiency, flea-beetle resistance, cold/freeze tolerance, and drought tolerance traits would have the largest economic impacts. Major beneficiaries of the surplus benefits are consumers as well as Canadian producers and innovators. The magnitudes of economic impacts varied substantially across the three major canola-growing Canadian provinces. Net benefits were sensitive to supply elasticity and R&D lags.

*Key words*: agricultural genomics, canola, molecular-assisted breeding, surplus analysis, trait evaluation

## Introduction

Significant investment in agricultural genomics research has occurred in the past ten years, particularly with regards to sequencing the genomes of model and commercially important crops. Globally, nearly 242 plant species have been or are being sequenced (National Center for Biotechnology Information, 2012). In Canada alone, publicly funded Genome Canada has spent approximately C$190 million since 2001–02 on fifteen large-scale agricultural genomics projects targeted to introduce new traits with the potential to increase the productivity and enhance the quality of agricultural crops (CanadaGE$^3$LS, 2011). The sequencing effort has enabled researchers to identify and isolate genes that code for traits that could overcome a variety of biotic and abiotic stresses, increasing yields and reducing production costs. In particular, genomics research has been used to identify suitable genetic markers that could be used in crop breeding through marker-assisted selection (MAS).[1]

Given the large amount of genomic data that has been assembled, molecular plant breeders now have the tools to develop plants with traits that would not be possible using conventional breeding alone. However the scarcity of research resources requires decisions to be made about which crops and traits to target as well as the appropriate techniques and protocols to employ in order to maximize social welfare. This paper presents the results of an exercise on trait evaluation for canola, an economically important crop for Canada. This study uses an economic surplus analysis to quantify a number of canola traits that have the potential to provide benefits.

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[1] Marker-aided selection (MAS) is a process that uses "markers" to identify a trait of interest (e.g., productivity, disease resistance, abiotic stress tolerance, quality). Markers are usually based on DNA/RNA variation, but can also be biochemical or morphological.

Multiple economic tools and methods exist to help decision makers assess the benefits of a project. The economic surplus approach is widely used because of its emphasis on meeting efficiency objectives. When efficiency is the main decision-making criterion, projects can be ranked according to the Net Present Value (NPV) method (Alston, Norton, and Pardey, 1995). Economic surplus models seek to capture—either *ex post* or *ex ante*—the magnitude of changes in welfare resulting from, for example, the introduction of a new technology. By making appropriate assumptions about the properties of the supply and demand functions and the nature of the technological change, it becomes possible to estimate the change in welfare. Economic surplus modeling has been used in cost benefit analysis and to identify investments that would yield the most benefit. Its use in research priority setting has been particularly useful for crop research in which multiple traits and crops need to be ranked on the basis of the potential benefits that could result from commercialization. Recent studies have evaluated the potential for agricultural biotechnology innovations in developing countries, where resources are particularly constrained and careful priority setting is needed (see Foltz, 2007; You and Johnson, 2010; Alpuerto et al., 2009; Rudi et al., 2010).

Surplus models have been particularly useful in estimating the distribution of benefits among different stakeholders. For example, Falck-Zepeda, Traxler, and Nelson (2000) examined the welfare effects from the introduction of Bt cotton in the United States and estimated a mean increase in world surplus of US$240.3 million, of which the largest share (59%) went to U.S. farmers. The innovator, Monsanto, received the next largest share (21%), followed by U.S. consumers (9%), the rest of the world (ROW) (6%), and the germplasm supplier, Delta and Pine Land Company (5%). Similar distributions of benefits have been observed for other plant biotechnologies in which farmers or producers captured most of the benefits (Qaim, 2003; Naseem and Pray, 2004).

Previous studies estimating welfare changes as a result of new canola traits have been limited to examining the impact of genetically modified herbicide-tolerance (HT) technology (or trait). In an evaluation of the welfare effects of HT canola in Canada, Phillips (2003) estimated that farmers received benefits of about C$8.40/acre—or about C$70 million in net returns, which comes to about 29% of total benefits. The largest share went to the innovators (at 57% of total benefits) and the smallest to consumers (14%). Similar estimates have been reached by LMC International (2011), which reported that direct producer benefits of HT canola averaged C$10.62/acre in 2000, yielding a net gain of C$66 million for producers.

This paper seeks to identify and estimate the impacts that the introduction of new canola traits would have on producers, consumers, and innovators. We take a decidedly Canadian perspective, not only because Canada is one of the largest producers of canola, but also because it is one of the leaders in canola R&D (Phillips and Khachatourians, 2001). The direction of future research will depend in part on the potential economic benefits of different traits. Our results will allow researchers, research managers, and policy makers to focus their research efforts on traits with the greatest potential impact on canola yield and farm receipts.

Although the primary objective of our analysis is to estimate the benefits of introducing novel traits in canola, we also estimate the ranges of impact after considering the correlation between yield improvements and adoption rates. A greater productivity increase as a result of a particular technology is likely to increase the adoption rate of that technology, resulting in benefits that occur earlier in time (Feder, Just, and Zilberman, 1985). We determine how large the impact (if any) of higher yields and faster adoption on benefits.

## Canola Traits

Canola varieties that are grown in Canada belong to either *Brassica napus* (99.5% of total canola area) or *Brassica rapa* (0.5% of total canola area) species.[2] Given the predominance of *B. napus*, we only gathered information on traits specific to this variety. We first identified all canola traits

[2] Based on personal communication with Mr. Clint Jurke, an Agronomy Specialist at the CCC.

**Table 1. Major Traits in Canola**

| Trait | Category | Commercialized (Yes/No) |
|---|---|---|
| Cold/Freeze Tolerance | Abiotic | No |
| Drought Tolerance | Abiotic | No |
| Heat-Blast Resistance | Abiotic | No |
| Soil-Salinity Tolerance | Abiotic | No |
| Sclerotina-Stem-Rot Resistance | Biotic | Yes |
| Blackleg Resistance | Biotic | Yes |
| Cutworm Resistance | Biotic | No |
| Flea-Beetle Resistance | Biotic | No |
| Nitrogen-Use Efficiency | Input | No |
| Water-Use Efficiency | Input | No |
| Seed-Size Improvement | Plant | No |
| Plant-Density Improvement | Plant | No |
| Pod-Shattering Resistance | Plant | No[a] |
| Early Maturity | Other | Yes |

*Notes:* [a]Will be commercialized soon.

with potential agronomic or economic value in the Canadian production environment based on information obtained from the canola growers' manual from the Canola Council of Canada (CCC) (Appendix A). The list was presented to canola agronomists at the CCC, who were asked to choose the traits that could be considered technically and commercially viable. Based on this information, we selected fourteen traits for further evaluation.

The traits under consideration fall in one of the following categories: traits that overcome particular stresses (either biotic or abiotic); traits that improve the efficiency of input use, primarily water and nitrogen; and traits that alter the physiology of the plant to increase yield or some other quality attribute (such as nutritional or oil content). Table 1 lists the fourteen traits according to this classification system and provides information on their commercialization status.

Since this study focuses on *ex ante* impacts of traits that have not been commercialized, we omit from further consideration sclerotina stem rot resistance, blackleg resistance, early maturity, and pod shattering resistance, since these are already under commercial production.

## Conceptual Framework

Economic surplus approaches are widely used to assess the desirability of investment projects (Alston, Norton, and Pardey, 1995). When efficiency is the main decision criteria, the NPV method with research investments that yield a positive NPV has the potential for Pareto improvement and efficiency gains. However, when faced with several mutually exclusive investments with positive NPVs, projects need to be ranked and the one with largest NPV chosen. We use a net benefits criterion to rank the benefits of different traits.

More specifically, we use economic surplus methods to evaluate the additional benefits received by society as a result of productivity increases (and related price decreases) or cost decreases from the introduction of new, research-based technologies (Alston, Norton, and Pardey, 1995; Ramasamy et al., 2007). This method accounts for the distribution of benefits in society by disaggregating the total change in surplus into consumer and producer surpluses. For the purposes of our model, we assume an open economy with price spillovers but no technology spillovers,[3] since more than 90% of the canola grown in Canada is exported and most of the traits under consideration are only

[3] Price spillovers occur when a technical change in one large country has an effect in other countries as a result of price changes. Technology spillovers arise when other countries are able to adopt research results from the country where the research is conducted.

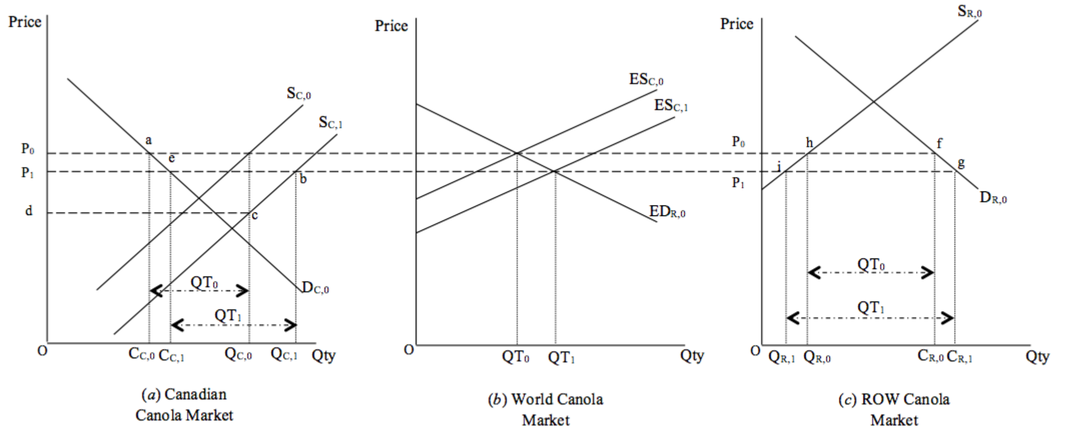


**Figure 1. Size and Distribution of Benefits of Research on Canola in Canada on the World (with Price Spillovers Only and No Technology Spillovers)**

*Notes:* Adapted from figure 4.2 of Alston, Norton, and Pardey (1995).

appropriate to Canadian agro-climatic conditions (Canola Council of Canada, 2011a). To analyze research-induced price spillovers, we model the worldwide canola market in terms of trade between a competitive, open-economy—such as Canada—and the rest of the world (ROW) as represented in figure 1. The price of canola is determined in the world market (panel b), which is an aggregation of supply and demand in Canada (panel a) and ROW (panel c). Excess supply of canola in Canada is shown as $ES_{C,0}$ in panel b and determined by the horizontal difference between domestic supply ($S_{C,0}$) and demand ($D_{C,0}$) in panel a. Likewise, excess demand in ROW is shown as $ED_{R,0}$ in panel b and determined by the difference in supply ($S_{R,0}$) and demand ($D_{R,0}$) in panel c. World canola-market equilibrium is established by the intersection of excess supply and demand at price $P_0$. The corresponding canola quantities in Canada are consumption, $C_{C,0}$, production, $Q_{C,0}$, and exports, $QT_0$; ROW quantities are consumption, $C_{R,0}$, production, $Q_{R,0}$, and imports, $QT_0$.

When a new technology is introduced, the supply curve in the Canadian canola market shifts from $S_{c,0}$ to $S_{c,1}$ (panel a), which shifts global supply from $ES_{c,0}$ to $ES_{c,1}$ (panel b). The new, lower equilibrium price is $P_1$. The corresponding quantities of canola in Canada are consumption, $C_{C,1}$ , production, $Q_{C,1}$, and exports, $QT_1$; ROW quantities are consumption, $C_{R,1}$, production, $Q_{R,1}$, and imports, $QT_1$. Consumers everywhere and producers in Canada are likely to gain, while ROW producers are likely to lose. This can be observed from figure 1, in which changes in consumer and producer surplus for Canada are represented by $P_0aeP_1$ and $P_1bcd$ and consumer surplus and producer loss for ROW are $P_0fgP_1$ and $P_0hiP_1$.

As the basis for surplus-analysis studies, this framework works best for production traits, not quality traits. Alpuerto et al. (2009) and Rudi et al. (2010) use it to evaluate the impact of MAS breeding research for rice and cassava, respectively. However, their estimates are based on the assumption that the technologies under consideration are forthcoming and will be adopted. Given the uncertainty inherent in generating new technologies, it is more appropriate to model the innovation process as stochastic. Zhao et al. (2000) and Falck-Zepeda, Traxler, and Nelson (2000) account for uncertainty by assuming some probability distributions for parameters like supply, demand, and trade elasticities while evaluating the economic impact of new technologies. We also incorporate uncertainty in our analysis and augment it by considering a possible correlation between the potential yield-change advantage of a new trait and its adoption rate.

Following Alston, Norton, and Pardey (1995), changes in consumer and producer surpluses in Canada and ROW after the introduction of a new trait (as shown in figure 1) are calculated as

(1) $$\Delta CS_{C,t} = P_0 C_{C,0} Z_t (1 + 0.5 Z_t \gamma_C);$$

(2) $$\Delta PS_{C,t} = P_0 Q_{C,0} (K_t - Z_t)(1 + 0.5 Z_t \varepsilon_C);$$

(3) $$\Delta CS_{R,t} = P_0 C_{R,0} Z_t (1 + 0.5 Z_t \gamma_R);$$

(4) $$\Delta PS_{R,t} = P_0 Q_{R,0} Z_t (1 + 0.5 Z_t \varepsilon_R);$$

where $\Delta CS_{C,t}$ is the change in consumer surplus in Canada in year $t$; $\Delta PS_C$ is change in producer surplus in Canada in year $t$; $\Delta CS_{R,t}$ is change in consumer surplus in ROW in year $t$; $\Delta PS_{R,t}$ is change in producer surplus in ROW in year $t$; $P_0$ is the equilibrium world price before the research; $C_{C,0}$ and $C_{R,0}$ are preresearch consumption of canola in Canada and ROW; $Q_{C,0}$ and $Q_{R,0}$ are preresearch productions of canola in Canada and ROW; $\gamma_C$ and $\gamma_R$ are elasticities of demand for canola in Canada and ROW; $\varepsilon_C$ and $\varepsilon_R$ are supply elasticities for canola in Canada and ROW; $K_t$ is the vertical shift of the supply function in year $t$, expressed as a proportion of the initial price; and $Z_t$ is the relative reduction in price in year $t$.

The vertical shift of the supply function at time $t$ ($K_t$) as given in equation (2) is calculated as

(5) $$K_t = \left[ \left( \frac{y_c}{\varepsilon_C} \right) - \left( \frac{E(Costs)}{1 + y_c} \right) \right] p A_t (1 - d_t),$$

where $y_c$ is the expected proportionate yield change; $E(Costs)$ is the expected proportionate change in variable input costs; $(\frac{y_c}{\varepsilon_C})$ converts the proportionate yield change to a proportionate gross reduction in marginal cost per unit of output; and $(\frac{E(Costs)}{1+y_c})$ converts proportionate input costs change per hectare to a proportionate input cost change per unit of output. Subtracting $(\frac{E(Costs)}{1+y_c})$ from $(\frac{y_c}{\varepsilon_C})$ gives the maximum potential net change in marginal cost per unit of output, which calculates to $K_t$ when multiplied by probability of success of the research ($p$), adoption rate ($A_t$), and the depreciation rate of new technology ($d_t$).[4]

Furthermore, $y_c$ is assumed to have a truncated normal distribution with mean $\mu_1$ and standard deviation $\sigma_1$, with values bounded between $a$ and $b$. Crop yields are usually assumed to have truncated normal distributions rather than standard normal distributions, because yields are bounded by zero on the downside and limiting nutrients (such as nitrogen) on the upside. Mathematically, $y_c$ is expressed as[5]

(6) $$y_c \sim N(\mu_1, \sigma_1^2), \text{ where } y_c \in (a, b).$$

$A_t$ defines the adoption pattern of technological innovation as a result of research, which is assumed to have a logistic path formulated as

(7) $$A_t = \left( \frac{A_{max}}{1 + e^{-(\alpha + \beta t)}} \right)$$

where $\alpha$ and $\beta$ are parameters that define the path of the adoption curve that asymptotically approaches the maximum.[6] $A_{max}$ is the maximum adoption possible, which is assumed to have a

[4] We assume that the new technology will become obsolete and be superseded as market conditions and technology change. The depreciation adjusts the expected research impact downward a few years after use of the new technology begins.

[5] For damage-abatement biotic traits in canola, the expected proportionate damage, $\phi_c$, is assumed to have a truncated normal distribution with mean $\mu_0$ and standard deviation $\sigma_0$, and whose values are bounded between minimum and maximum values represented by $e$ and $f$. Mathematically, $y_c$ is expressed as $\phi_c \sim N(\mu_0, \sigma_o^2)$, where $\phi_c \in (e, f)$. Finally, $y_c$ is calculated as $y_c = \frac{\phi_c}{1-\phi_c}$.

[6] While $\alpha$ represents a shift in adoption curve, $\beta$ represents the growth rate of the adoption curve. These two parameters can be estimated if we know $A_{max}$ and any two combinations of $A_t$ and $t$.

continuous uniform probability distribution with minimum and maximum values represented by $c$ and $d$:

$$A_{max} \sim U(c,d). \tag{8}$$

Expected yield change and maximum adoption are assumed to be positively correlated with a correlation coefficient of $\rho$:

$$Corr(y_c, A_{max}) = \rho. \tag{9}$$

Equation (9) incorporates our view that expected yield change and maximum adoption are positively correlated, because higher yield-change (or cost-change) expectations from a new technology would likely to result in its higher adoption (Feder, Just, and Zilberman, 1985).

Following Alston, Norton, and Pardey (1995), we calculate the relative reduction in price at time $t$ ($Z_t$) used in equations (1)–(4) as

$$Z_t = \varepsilon_C K_t / [\varepsilon_C + s_C \gamma_C + (1 - s_C)\gamma_R^E], \tag{10}$$

where $s_C$ is the fraction of canola production that is consumed domestically and $\gamma_R^E$ is the excess demand elasticity for canola in ROW (or export demand for canola in Canada), which is calculated as

$$\gamma_R^E = \left(\frac{Q_{R,0}}{C_{R,0} - Q_{R,0}}\right) \times \varepsilon_R + \left(\frac{C_{R,0}}{C_{R,0} - Q_{R,0}}\right) \times \gamma_R \tag{11}$$

The new trait is likely to be protected by some form of intellectual property right—such as a patent or plant variety protection certificate—which would generate monopoly profits for the innovators. Using the Moschini and Lapan (1997) framework for analyzing welfare effects of proprietary technologies, we follow Falck-Zepeda, Traxler, and Nelson (2000) and Hareau, Mills, and Norton (2006) to calculate monopoly profits or surplus for the innovator of a technology in year $t$:

$$\Delta IS_t = \mu \times A_t \times L_t, \tag{12}$$

where $\mu$ is the technology fee per acre, which is calculated as a difference in seed costs per acre of a new variety and a conventional variety; $A_t$ is the adoption rate of (or proportion of area under) a new technology in year $t$; and $L_t$ is the corresponding area under canola production in year $t$. Since the new traits in canola are mostly suited to the Canadian agro-climate, we assume that most of the research will be performed by Canadian innovators. We assume that the entire innovator's surplus would be received by Canadian innovators.

Summing up, changes in total surplus in Canada ($\Delta TS_{C,t}$) and ROW ($\Delta TS_{R,t}$) in year $t$ are given by

$$\Delta TS_{C,t} = \Delta CS_{C,t} + \Delta PS_{C,t} + \Delta IS_t; \tag{13}$$

$$\Delta TS_{R,t} = \Delta CS_{R,t} + \Delta PS_{R,t}. \tag{14}$$

Changes in total global surplus in year t are calculated by summing the total surplus in Canada and ROW:

$$\Delta TS_{Global,t} = \Delta TS_{C,t} + \Delta TS_{R,t}. \tag{15}$$

Finally, we calculate the net present value (NPV) of the annual global surplus as

$$NPV = \sum_{t=0}^{T} \frac{\Delta TS_{Global,t} - RCost_t}{(1+r)^t}, \tag{16}$$

where $T$ is the time-horizon, $RCost_t$ is research costs in year $t$, and $r$ is the discount rate.

## Data and Parameters

Parameter values and changes in relevant variables were obtained through the Delphi Method: we obtained forecasts for the ten shortlisted traits from canola agronomists, breeders, and scientists. An online survey was sent to thirty individuals during the summer of 2011. We received twelve responses (40% response rate), which equally represented the three canola-growing Canadian provinces (Alberta, Saskatchewan, and Manitoba). Wherever possible, the parameter values and forecasts were cross-referenced with information from the literature.

Table 2 lists the major model parameters and their values obtained from the online survey and various published sources. Of the biotic traits, yield loss due to a biotic stress and canola area affected by that stress are reported. Incidences and severity of insects and disease attack were reported to be highest in Saskatchewan, followed by Alberta and Manitoba. Yield loss due to abiotic stresses—such as cold and draught tolerance—and the area affected by those stresses were highest in Alberta, followed by Saskatchewan and Manitoba. The additional area that could come under canola cultivation after adopting traits such as cold tolerance, drought tolerance, and soil salinity tolerance is also reported in table 2. Saskatchewan is expected to have a 1% annual increase in canola area as a result of introducing canola varieties that can withstand cold/freeze stress. Across the prairies, the expected increase in canola yield as a result of increased NUE is about 20–30%. Yield increases due to increased WUE are expected to be 20–30% in Alberta, which is relatively higher than in Saskatchewan and Manitoba. Plant traits such as seed-size improvement and plant-density improvement were expected to produce relatively small yield increases.

Data on canola acreage and yield at the provincial level were obtained from the Canola Council of Canada. Table 3 shows average acreage and yield of canola seed in Canada for the last four years (2007–08 to 2010–11).

Because expectations of higher yield increase from a technology are likely to spur its adoption rate, we assume a strong correlation ($\rho = 0.8$) between the expected yield change as a result of new technology and its adoption rate. The value of the correlation coefficient was subjected to sensitivity analysis. Given that the state of knowledge in introducing different traits varies considerably, the probability of research success is likely to vary across traits. We assume a 50% research success rate for the traits, because the scientists we surveyed could not assign specific values for the probability of research success for the listed traits. Based on the adoption pattern of various genetically modified traits in the United States and Canada, we assume that adoption will follow logistic growth. We project that adoption will reach its maximum level in seven years, maintain that level for the next four years, and then decline linearly to zero in the next four years as existing traits are gradually replaced by new traits. Given the public nature of the canola varieties that are expected to be developed using the current publically funded genomics research on canola, we assume that half of the maximum adoption level would be reached in three years.[7] Table 4 lists the ranges of maximum adoption rate at the provincial level for different categories of traits obtained from our survey. Adoption rates were relatively higher in Alberta and Saskatchewan because of favorable conditions for canola cultivation in those regions. Moreover, survey respondents indicated that abiotic traits (such as cold and drought tolerance) and biotic traits (cutworm and flea-beetle resistance) are likely to be adopted more widely in comparison to plant and input traits.

Supply elasticity estimates for Canada and ROW were assumed to be 0.85 and 0.58 (Johnson et al., 1996; International Monetary Fund, 2008). The supply elasticity value for Canada is subjected to sensitivity analysis. Demand elasticities of -1.14 and -0.73 for Canada and ROW are based on averages of various demand elasticity estimates (Johnson et al., 1996; Goddard and Glance, 1989; Meilke and Griffith, 1981; Spriggs, 1981; Kolody, 1990; Nagy and Furtan, 1978; Phillips, 2003;

[7] Privately developed Herbicide-Tolerant (HT) canola was adopted very rapidly in Canada, and the adoption reached 50% of the maximum adoption in just two years. This high adoption rate was the result of aggressive marketing by public corporations such as Monsanto and AgrEvo (Personal Communication with Dr. Peter Phillips, professor of Public Policy at the University of Saskatchewan).

**Table 2. Model Parameters Obtained from the Online Survey and Published Sources**

| | | Online Survey Figures | | | |
|---|---|---|---|---|---|
| **Trait** | **Parameter** | **AB** | **SK** | **MB** | **Published Values (Source)** |
| Cold/Freeze Tolerance | Yield loss due to cold (%) | 23–30 | 10–15 | 10–15 | – |
| | Annual acreage expansion (%) | 3 | 1 | 0 | – |
| | Affected acreage (%) | 50 | 50 | 0 | – |
| Drought Tolerance | Yield loss due to drought (%) | 25–32 | 12–17 | 10–15 | – |
| | Annual acreage expansion (%) | 3.5 | 2 | 1 | – |
| | Affected acreage (%) | 40 | 22.5 | 15 | – |
| Heat-Blast Resistance | Yield loss due to heat blast (%) | 12.5–15.0 | 11–15 | 5–6 | 10-20% (CCC, 2012) |
| | Affected area (%) | 60 | 30 | 10 | – |
| Soil-Salinity Tolerance | Yield loss in salt-affected soils (%) | 11–15 | 2.5–3.5 | 2.5–3.5 | – |
| | Annual acreage expansion (%) | 1 | 0.5 | 0 | – |
| | Affected area (%) | 25 | 10 | 5 | AB: 31.27, SK: 43.89, MB:19.38 (Govt. of Alberta, 2010) |
| Cutworm Resistance | Yield loss due to cutworm (%) | 5–6 | 4–5 | 1.5–1.6 | – |
| | Affected area (%) | 40 | 60 | 50 | – |
| Flea-Beetle Resistance | Yield loss due to flea beetles (%) | 8.5–9.5 | 12–14 | 1.5–2.5 | 8-10[a] (Lamb and Turnock, 1982) |
| | Affected area (%) | 60 | 75 | 50 | – |
| Nitrogen-Use Efficiency | Yield increment (%) | 20–25 | 20–30 | 20–30 | 20-30[b] (Dansby, 2008) |
| Water-Use Efficiency | Yield increment (%) | 20-30 | 10-20 | 10-15 | - |
| Seed-Size Improvement | Seed size increment (%) | 3-4 | 4-5 | 0.5-1.0 | - |
| Plant-Density Improvement | Yield increment (%) | 2.0-2.5 | 2.0-2.5 | 1.0-1.5 | - |

*Notes:* A range of expected yield change indicates upper and lower bounds of a truncated normal probability distribution.
[a] Overall figure for the prairies.
[b] Values are for U.S. canola.

Burton, Salisbury, and Potts, 2003; Mayer and Furtan, 1999; International Monetary Fund, 2008). We tried to replicate the Kolody (1990) and Nagy and Furtan (1978) model using updated time-series data from 1985–2011 and found a very inelastic demand elasticity estimate, the magnitude of which was very different from the elastic demand elasticity estimated by those researchers using past data. As demand can be more elastic in a very long-run scenario because of the substitutability of canola oil with other vegetable oils, we tested the sensitivity of results using relatively higher values for demand elasticities.

Table 5 presents the values and sources of parameters such as R&D lags, R&D costs, demand and supply elasticities, prices, demands, discount rate, and technology fee. McDougall (2011) reports that new canola traits require an average of twelve years and C$136[8] million to develop (after

[8] This figure was originally reported in U.S. dollars; it was converted to Canadian currency using 1:1 exchange rate prevailing at that time.

**Table 3. Average Acreage and Yield of Canola Seed in Canada**

| Province | Acreage (in thousands) | Yield (tonnes/acre) |
|---|---|---|
| Alberta | 5117.50 | 0.77 |
| Saskatchewan | 7518.80 | 0.70 |
| Manitoba | 3096.30 | 0.78 |
| Other | 51.25 | 0.72 |

*Source:* (Canola Council of Canada, 2011b)

**Table 4. Maximum Percentage Adoption Rates for Different Categories of Traits**

| Province | Abiotic Traits | Biotic Traits | Input Traits | Plant Traits |
|---|---|---|---|---|
| Alberta | 80–90 | 75–85 | 70–80 | 70–80 |
| Saskatchewan | 80–90 | 80–90 | 60–70 | 80–90 |
| Manitoba | 50–60 | 65–75 | 50–60 | 50–60 |
| Other | 50–60 | 55–65 | 50–60 | 20–30 |

*Notes:* A range of expected adoption depicts lower and upper bounds of a uniform probability distribution.
*Source:* Delphi survey conducted by authors.

**Table 5. Baseline Model Parameter Values**

| Parameter | Value | Source |
|---|---|---|
| Demand elasticity, Canada | −1.14 | Johnson et al. (1996); Goddard and Glance (1989); Meilke and Griffith (1981); Spriggs (1981); Kolody (1990); Nagy and Furtan (1978); Phillips (2003); Burton, Salisbury, and Potts (2003); Mayer and Furtan (1999) |
| Supply elasticity, Canada | 0.85 | Johnson et al. (1996); Santaniello, Evenson, and Zilberman (2002) |
| Demand elasticity, ROW | −0.73 | Johnson et al. (1996); Goddard and Glance (1989); Meilke and Griffith (1981); International Monetary Fund (2008) |
| Supply elasticity, ROW | 0.58 | International Monetary Fund (2008) |
| R&D lags (years) | 12.00 | McDougall (2011) |
| Average canola seed price/tonne ($) | 473.00 | Canola Council of Canada (2011b) |
| Domestic demand (million tonnes) | 4.50 | Foreign Agricultural Service, USDA |
| ROW demand (million tonnes) | 33.00 | Foreign Agricultural Service, USDA |
| Discount rate (%) | 3.50 | Boardman and Moore (2010) |
| R&D costs (millions C$) | 136.00 | McDougall (2011) |
| Technology fee ($/acre) | 16.34 | Dawson (2011) |

accounting for lags in obtaining regulatory approval). We use these estimates for our analysis as well.

We assume a canola seed price of C$450/tonne, which is the average for the period from 2007–08 to 2010–11 (Canola Council of Canada, 2011b). Average annual consumption of canola in Canada and ROW was 4.5 and 33 million tonnes (U.S. Department of Agriculture, Foreign Agricultural Service, 2011). A long-term social-discount rate of 3.5% was assumed for the analysis (Boardman and Moore, 2010).

Total variable cost of cultivation was assumed to be C$105.17 per acre for conventional canola (Canola Council of Canada, 2010). Since none of the traits have been commercialized, we assume that any technology fee would be in line with previous fees, such as that for herbicide-tolerant technology ($12.55–$18.50/acre). For our model we choose a technology fee of C$16.34/acre, the latest technology fee estimate reported by Monsanto (Dawson, 2011). The cost of harvesting additional production (due to new technology) is assumed to be 1% of the total cost of cultivation. Based on estimates from reduction in pesticide use on Bt crops, the reduction in the cost of

**Table 6. Gross and Net Discounted Global Economic Impacts (Millions C$) of Major Traits in Canola**

| Class | Trait | Min. Impact | Max. Impact | Avg. Impact | Std. Dev. | Coeff. of Variation | Avg. Net Impact |
|---|---|---|---|---|---|---|---|
| Abiotic | Cold/Freeze Tolerance | 1162.41 | 2073.12 | 1568.54 | 237.49 | 15.14 | 1432.54 |
| | Drought Tolerance | 1072.02 | 1965.90 | 1470.25 | 234.08 | 15.92 | 1334.25 |
| | Heat Blast resistance | 597.81 | 116.69 | 850.61 | 149.40 | 17.56 | 714.61 |
| | Soil Salinity Tolerance | 325.24 | 783.99 | 528.85 | 122.42 | 23.15 | 392.85 |
| Biotic | Cutworm Resistance | 631.54 | 822.34 | 718.46 | 45.15 | 6.28 | 582.46 |
| | Flea-Beetle Resistance | 1353.07 | 1863.39 | 1583.71 | 124.94 | 7.89 | 1447.71 |
| Input | Nitrogen Use Efficiency | 2210.12 | 3412.09 | 2748.18 | 298.81 | 10.87 | 2612.18 |
| | Water Use Efficiency | 1477.36 | 2605.69 | 1979.26 | 288.25 | 14.56 | 1843.26 |
| Plant | Seed Size Improvement | 725.64 | 940.56 | 824.20 | 48.68 | 5.91 | 688.20 |
| | Plant Density Improvement | 249.45 | 522.48 | 370.72 | 70.02 | 18.89 | 234.72 |

*Notes:* Average net impact is calculated as average impact minus a constant research cost of C$136 million for a single canola trait.

insecticide use in the case of biotic traits is assumed to be 5% of the total cost (Qaim and Zilberman, 2003).

## Results

For each trait, 10,000 iterations of simulations were conducted using Monte Carlo methods after assuming a joint distribution of the parameters of yield change and maximum adoption.

### *Gross and Net Economic Benefits from New Traits*

Table 6 shows the ranges of gross expected returns from introducing the ten new traits under the baseline parameter values assumptions.[9] The table also shows the net return calculations after including R&D costs incurred in developing and introducing a new trait in canola. The results depict the most likely scenario, but we did examine the sensitivity of the results to major model parameters. Globally and in Canada, the NUE trait had the highest returns (and a lower CV) because of expectations of a higher yield (20–30%) increase due to broad adoption of the NUE trait. Other traits with significant potential economic returns are WUE, flea-beetle resistance, cold/freeze tolerance, drought tolerance, heat-blast resistance, and seed-size improvement.

Our estimates suggest that all traits will likely generate positive benefits. An improvement in NUE in canola has the potential to generate average returns of C$2,210.12–3,412.09 million globally, with an average of C$2,748.18 million. These returns include benefits received by producers, consumers, and technology innovators. Moreover, the average returns from improved NUE have the second lowest dispersion around the mean (the lowest coefficient of variation is of net returns from varieties with improved seed size). Average net returns from NUE after accounting for fixed R&D costs of C$136 million were C$2,612.18 million. Improvements in WUE in canola have the potential to generate average benefits of C$1477.36–2605.69 million. The corresponding ranges of average returns generated from flea-beetle resistance, cold/freeze tolerance, and drought tolerance varieties were C$1,353.07–1,863.39, C$1,162.41–2,073.12, and C$1,072.02–1,965.90 million. While average returns from varieties resistant to heat blast (C$850.61 million) were higher than those with improved seed size (C$824.20 million), returns from the latter type of varieties have a much lower CV (48.68%) compared to the former type of varieties (149.40%). Varieties resistant

[9] Detailed calculations for a given trait (e.g., cold tolerance) are presented in Appendix B.

**Table 7. Welfare Effects (Millions of C$) of Major Traits in Canola under Baseline Model Assumptions**

| | | Consumer Surplus | | Producer Surplus | | Innovator |
|---|---|---|---|---|---|---|
| **Class** | **Trait** | **Canada** | **ROW** | **Canada** | **ROW** | **Rents** |
| Abiotic | Cold/Freeze Tolerance | 81.84 | 901.29 | 781.77 | −669.76 | 473.40 |
| | Drought Tolerance | 90.08 | 991.95 | 810.31 | −737.02 | 314.93 |
| | Heat-Blast Resistance | 39.49 | 438.51 | 276.44 | −326.10 | 422.27 |
| | Soil-Salinity Tolerance | 17.46 | 192.43 | 49.98 | −143.14 | 412.12 |
| Biotic | Cutworm Resistance | 14.13 | 155.75 | 57.08 | −115.89 | 607.39 |
| | Flea-Beetle Resistance | 75.93 | 836.47 | 524.38 | −621.65 | 768.58 |
| Input | Nitrogen-Use Efficiency | 128.40 | 1412.76 | 1287.90 | −1048.98 | 968.10 |
| | Water-Use Efficiency | 15.92 | 791.60 | 749.84 | −546.20 | 968.10 |
| Plant | Seed-Size Improvement | −6.23 | −68.74 | −120.10 | 51.17 | 968.10 |
| | Plant-Density Improvement | −32.93 | −363.57 | −471.65 | 270.77 | 968.10 |

to cutworm or with the ability to tolerate soil salinity are also likely to generate significant benefits. The plant-density-improvement trait has the smallest economic return.

*Welfare Effects of New Traits*

The question of who benefits from a new technology is of considerable importance. Table 7shows that the major beneficiaries of the introduction of most new traits are Canadian producers, consumers, and innovators as well as ROW consumers. However, ROW producers will see a net loss as a result of a reduction in world canola prices caused by an increase in world canola supply. ROW consumers see the largest benefit because a large population of world canola consumers would realize a reduction in world canola prices. Introducing varieties with the NUE trait, for instance, is likely to increase the surplus of Canadian canola producers and consumers by an average C$1,287.90 million and C$128.40 million, respectively. ROW consumers are likely to gain an average C$1,412.76 million; however, ROW producers are expected to lose C$1,048.98 million after the introduction of the NUE trait in canola. Falck-Zepeda, Traxler, and Nelson (2000) found similar effects when evaluating the welfare effects of Bt cotton technology in the United States.

Canadian producers, Canadian consumers, and ROW consumers received negative benefits for traits such as improvements in seed size and plant density; for these traits, the total technology costs (innovator rents) were greater than the expected revenues generated from an increase in canola yield after the introduction of these traits. Innovators of these technologies are expected to gain C$968.10 million for each technology, and ROW producers are also likely to gain as a result of higher world prices. Innovator rents are calculated as the product of the technology fee and the canola area that is expected to be adopted under new technology. Returns are expected to be highest (around C$968 million) for traits in the input and plant categories because Canadian producers will likely adopt these traits countrywide. However, innovator rents for soil salinity, for instance, are only C$412.12 million, because the constrained acreage (i.e., the area affected by soil salinity) is only a small proportion of the area under canola production in Canada.

*Regional Distribution of Benefits across Canada*

Gross benefits were evaluated separately for three prairie provinces in order to account for regional differences in agro-climatic conditions for Canadian canola production. Tables 8, 9, and 10 present

**Table 8. Gross Discounted Economic Impacts (Millions of C$) of Major Traits in Canola in Alberta**

| Class | Trait | Min. Impact | Max. Impact | Avg. Impact | Std. Dev. | Coeff. of Variation |
|---|---|---|---|---|---|---|
| Abiotic | Cold/Freeze Tolerance | 445.55 | 735.47 | 575.07 | 74.93 | 13.03 |
| | Drought Tolerance | 435.86 | 723.29 | 564.23 | 74.36 | 13.18 |
| | Heat-Blast Resistance | 165.42 | 273.43 | 213.69 | 27.94 | 13.08 |
| | Soil-Salinity Tolerance | 52.80 | 198.45 | 117.22 | 39.64 | 33.82 |
| Biotic | Cutworm Resistance | 14.97 | 32.26 | 22.65 | 4.60 | 20.31 |
| | Flea-Beetle Resistance | 119.17 | 171.68 | 142.80 | 13.16 | 9.22 |
| Input | Nitrogen-Use Efficiency | 321.02 | 512.50 | 406.49 | 48.24 | 11.87 |
| | Water-Use Efficiency | 300.73 | 619.23 | 441.56 | 83.26 | 18.86 |
| Plant | Seed-Size Improvement | −45.32 | −33.23 | −39.66 | 2.93 | –[a] |
| | Plant-Density Improvement | −163.06 | −147.02 | −155.34 | 3.31 | –[a] |

*Notes:* [a]Not defined.

provincial evaluations of gross discounted economic impacts of major canola traits. Traits with the highest economic impact are cold/freeze tolerance, drought tolerance, NUE, and WUE in Alberta; NUE, flea-beetle resistance, cold/freeze tolerance, WUE, and drought tolerance in Saskatchewan; and NUE, WUE, and drought tolerance in Manitoba. Introducing NUE and WUE traits in canola will likely generate significant economic benefits in all three provinces because all three provinces are likely to adopt these traits, which will likely increase canola yields significantly.

The ten new traits have significant differences in economic benefits across the three provinces because of spatial variations in biotic and abiotic stresses across the Canadian prairies. For example, the expected benefits realized after the introduction of cold/freeze tolerance trait are highest in Alberta, followed by Saskatchewan and Manitoba, because the cold-prone acreage under canola production is high in the northwestern regions of Alberta and decreases toward the southeast (i.e., toward Manitoba).

Economic benefits are generally much lower in Manitoba than in Alberta and Saskatchewan, likely because canola yields are relatively higher in Manitoba, where comparatively minor yield increment can be achieved. In Alberta, improvements in cold/freeze tolerance, drought tolerance, NUE, and WUE are expected to generate average discounted benefits of C$575.07, C$564.23, C$406.49, and C$441.56 million. Average potential benefits expected in Saskatchewan are C$617.45, C$400.27, C$237.52, C$239.83, and C$208.74 million after improvements in NUE, flea-beetle resistance, cold/freeze, WUE, and drought tolerance. In Manitoba, where canola yield levels are significantly higher than in Alberta and Saskatchewan, average expected discounted benefits from introducing NUE, WUE, and drought tolerance are C$284.91, C$73.05, and C$50.33 million.

### *Sensitivity Analysis*

We conducted sensitivity analyses for some important parameters—such as R&D lags, demand elasticity, and supply elasticity—to evaluate how average benefits vary with changes in these parameters. Moreover, the impacts were evaluated under scenarios of zero correlation (between adoption rate and expected yield change) and alternative probability distribution of adoption rate. The impacts were not sensitive to demand elasticities, but they were sensitive to the higher supply elasticity value and R&D lags. Additionally, the impacts were insensitive to the correlation coefficient between adoption rate and expected yield change.

**Table 9. Gross Discounted Economic Impacts (Millions of C$) of Major Traits in Canola in Saskatchewan**

| Class | Trait | Min. Impact | Max. Impact | Avg. Impact | Std. Dev. | Coeff. of Variation |
|---|---|---|---|---|---|---|
| Abiotic | Cold/Freeze Tolerance | 130.37 | 372.30 | 237.52 | 65.35 | 27.51 |
| | Drought Tolerance | 103.69 | 341.10 | 208.74 | 64.41 | 30.86 |
| | Heat-Blast Resistance | 23.65 | 208.37 | 105.19 | 50.79 | 48.28 |
| | Soil-Salinity Tolerance | −62.39 | −18.72 | −42.20 | 11.93 | –[a] |
| Biotic | Cutworm Resistance | 25.98 | −47.16 | 35.42 | 5.55 | 15.67 |
| | Flea-Beetle Resistance | 342.31 | 470.63 | 400.27 | 31.63 | 7.90 |
| Input | Nitrogen-Use Efficiency | 421.17 | 864.93 | 617.45 | 116.13 | 18.81 |
| | Water-Use Efficiency | 72.56 | 454.09 | 239.83 | 103.97 | 43.35 |
| Plant | Seed-Size Improvement | −44.94 | −30.62 | −38.25 | 3.58 | –[a] |
| | Plant-Density Improvement | −213.67 | −197.67 | −205.84 | 3.54 | –[a] |

*Notes:* [a]Not defined.

**Table 10. Gross Discounted Economic Impacts (Millions of C$) of Major Traits in Canola in Manitoba**

| Class | Trait | Min. Impact | Max. Impact | Avg. Impact | Std. Dev. | Coeff. of Variation |
|---|---|---|---|---|---|---|
| Abiotic | Cold/Freeze Tolerance | −64.51 | 36.67 | −18.65 | 28 | –[a] |
| | Drought Tolerance | 4.05 | 108.97 | 50.33 | 28.96 | 57.54 |
| | Heat-Blast Resistance | −50.38 | −29.83 | −40.83 | 5.40 | –[a] |
| | Soil-Salinity Tolerance | −50.63 | −30.11 | −41.09 | 5.40 | –[a] |
| Biotic | Cutworm Resistance | −0.76 | 0.74 | −0.09 | 0.42 | –[a] |
| | Flea-Beetle Resistance | −17.61 | 3.51 | −7.96 | 5.85 | –[a] |
| Input | Nitrogen-Use Efficiency | 194.60 | 398.78 | 284.91 | 53.42 | 18.75 |
| | Water-Use Efficiency | 33.45 | 123.60 | 73.05 | 24.34 | 33.32 |
| Plant | Seed-Size Improvement | −44.12 | −40.96 | −42.57 | 0.72 | –[a] |
| | Plant-Density Improvement | −115.49 | −107.61 | −111.61 | 1.83 | –[a] |

*Notes:* [a]Not defined.

Magnitudes of impacts were sensitive to the number of years in R&D for all the traits, as shown in table 11. For the NUE trait, a decrease in the R&D lag period of one year (from twelve to eleven years) led to a rise in average benefits of C$96.19 million (from C$2748.18 to C$2844.37 million). On the other hand, an increase in the R&D lag period of one year (from twelve to thirteen years) led to a drop in average benefits of C$92.93 million (from C$2748.18 to C$2655.25 million). We assume that time horizon extended by a year with an extra year in R&D. The magnitudes of net benefits were also sensitive to R&D lags for other traits.

Considering that the price of canola oil relative to soya and other oils has not changed in the last decade—in spite of a doubling of canola oil production—[10] we assume an inelastic long-run supply of canola for Canada. Regardless, we conducted sensitivity analysis for the supply elasticity parameter. The long-run benefits decreased with an assumption of greater supply elasticity of canola

[10] The ratio of prices of canola oil/soya oil changed from 1.092 to 1.077, and ratio of prices of canola oil/palm oil changed from 1.303 to 1.344, from 1999 to 2012 (Index Mundi, 2013).

**Table 11. Gross Discounted Global Economic Impacts (Millions of C$) of Major Traits in Canola as Number of Years in R&D Varies**

| Class | Trait | R&D Lags = 11 | R&D Lags = 12 | R&D Lags = 13 |
|---|---|---|---|---|
| Abiotic | Cold/Freeze Tolerance | 1623.44 | 1568.54 | 1515.49 |
| | Drought Tolerance | 1499.31 | 1470.25 | 1399.63 |
| | Heat-Blast Resistance | 880.38 | 850.61 | 821.85 |
| | Soil-Salinity Tolerance | 547.36 | 528.85 | 510.96 |
| Biotic | Cutworm Resistance | 743.61 | 718.46 | 694.17 |
| | Flea-Beetle Resistance | 1639.14 | 1583.71 | 1530.16 |
| Input | Nitrogen-Use Efficiency | 2844.37 | 2748.18 | 2655.25 |
| | Water-Use Efficiency | 2048.53 | 1979.26 | 1912.33 |
| Plant | Seed-Size Improvement | 853.04 | 824.20 | 796.33 |
| | Plant-Density Improvement | 383.70 | 370.72 | 358.19 |

**Table 12. Gross Discounted Global Economic Impacts (Millions of C$) of Major Traits in Canola as the Supply Elasticity of Canola for Canada Varies**

| Class | Trait | SE = 0.26 | SE = 0.85 | SE = 1.00 | SE = 1.50 |
|---|---|---|---|---|---|
| Abiotic | Cold/Freeze Tolerance | 1525.25 | 1568.54 | 1556.56 | 1069.68 |
| | Drought Tolerance | 1429.67 | 1470.25 | 1459.02 | 987.05 |
| | Heat-Blast Resistance | 827.13 | 850.61 | 844.11 | 579.59 |
| | Soil-Salinity Tolerance | 514.25 | 528.85 | 524.81 | 358.94 |
| Biotic | Cutworm Resistance | 698.63 | 718.46 | 712.97 | 673.33 |
| | Flea-Beetle Resistance | 1540.00 | 1583.71 | 1571.61 | 1273.13 |
| Input | Nitrogen-Use Efficiency | 2672.33 | 2748.18 | 2727.19 | 1915.89 |
| | Water-Use Efficiency | 1924.63 | 1979.26 | 1964.14 | 1379.25 |
| Plant | Seed-Size Improvement | 801.45 | 824.20 | 817.90 | 765.46 |
| | Plant-Density Improvement | 360.49 | 370.72 | 367.89 | 265.21 |

in Canada. With an increase in the supply elasticity of canola from a baseline of 0.85 to 1.50, the average benefits drop significantly for most of the traits, as shown in table 12. For instance, the average benefits dropped from C$2727.19 million to C$1915.89 million with an increase in supply elasticity from 0.85 to 1.5 for the NUE trait. When supply was inelastic, the average benefits were not very different from the baseline for all the traits, with the average benefits decreasing only slightly from C$2727.19 to C$2672.33 million with a decrease in supply elasticity from the baseline of 0.85 to 0.26.[11] For the other traits, the benefits under lower supply elasticity were also not very sensitive to supply elasticity.

Table 13 presents the results of the sensitivity analysis of average benefits to parameters of demand elasticities. The results were not sensitive to demand elasticities. For the case of the NUE trait, average benefits decreased by only C$47.40 million (from C$2748.18 million to C$2700.78) when canola demand elasticities increased from -1.14 (baseline) to -1.5 for Canada and -0.73

[11] In the case of linear supply functions, the surplus benefits may be overestimated when supply is very inelastic because extrapolating back to the origin implies a negative intercept on the price axis. To fix this problem, the coefficients of relative proportions of surpluses (below and above the x-axis, representing canola quantity) were simulated for different values of inelastic supplies, and the surplus benefits were adjusted using these coefficients.

**Table 13. Gross Discounted Economic Impacts (Millions of C$) of Major Traits in Canola for Different Demand Elasticities**

| Class | Trait | $DE_C$ = -1.14 $DE_R$= -0.73 | $DE_C$ = -1.50 $DE_R$= -1.50 | $DE_C$ = -2.00 $DE_R$= -2.00 |
|---|---|---|---|---|
| Abiotic | Cold/Freeze Tolerance | 1568.54 | 1538.24 | 1520.43 |
| | Drought Tolerance | 1470.25 | 1419.49 | 1410.20 |
| | Heat-Blast Resistance | 850.61 | 828.66 | 812.14 |
| | Soil-Salinity Tolerance | 528.85 | 512.29 | 499.61 |
| Biotic | Cutworm Resistance | 718.46 | 703.59 | 698.80 |
| | Flea-Beetle Resistance | 1583.71 | 1542.18 | 1509.02 |
| Input | Nitrogen-Use Efficiency | 2748.18 | 2700.78 | 2678.90 |
| | Water-Use Efficiency | 1979.26 | 1952.90 | 1965.37 |
| Plant | Seed-Size Improvement | 824.20 | 812.41 | 819.15 |
| | Plant-Density Improvement | 370.72 | 362.48 | 367.58 |

**Table 14. Gross Discounted Global Economic Impacts (Millions of C$) of Major Traits in Canola as Distribution of Adoption Parameter, and its Correlation with Expected Yield Change Varies**

| Trait | $A_{max}$: Uniform $y_c$: TrunNor $\rho = 0.8$ | $A_{max}$: Uniform $y_c$: TrunNor $\rho = 0.0$ | $A_{max}$: TrunNor $y_c$: TrunNor $\rho = 0.8$ | $A_{max}$ : TrunNor $y_c$: TrunNor $\rho = 0.0$ |
|---|---|---|---|---|
| Cold/Freeze Tolerance | 1568.54 | 1562.36 | 1576.24 | 1549.63 |
| Drought Tolerance | 1470.25 | 1417.66 | 1478.44 | 1452.42 |
| Heat-Blast Resistance | 850.61 | 846.33 | 858.65 | 837.88 |
| Soil-Salinity Tolerance | 528.85 | 524.75 | 540.33 | 517.36 |
| Cutworm Resistance | 718.46 | 714.66 | 715.61 | 706.19 |
| Flea-Beetle Resistance | 1583.71 | 1577.76 | 1585.78 | 1564.73 |
| Nitrogen-Use Efficiency | 2748.18 | 2736.93 | 2749.52 | 2708.49 |
| Water-Use Efficiency | 1979.26 | 1970.21 | 1984.58 | 1948.15 |
| Seed-Size Improvement | 824.20 | 819.08 | 822.25 | 805.56 |
| Plant-Density Improvement | 370.72 | 341.94 | 433.12 | 286.07 |

*Notes:* "TrunNor" stands for truncated normal probability distribution.

(baseline) to -1.5 for ROW. Even with an increase in both the demand elasticities to -2.0, average benefits decreased by only C$69.28 million, from the baseline elasticity to C$2678.90 million.

Table 14 presents average benefits under baseline and alternative probability distribution assumptions for adoption rate, with and without a correlation between adoption rate and expected yield change. Average benefits didn't change much from the baseline when adoption rate was assumed to have a truncated normal probability distribution instead of baseline uniform probability distribution because of the symmetric nature of both distributions. The mean of a large random draws from a symmetric distribution will approach the midpoint value of the probability distribution interval, which in this case lies between 0 and 1.

Additionally, benefits only changed marginally from the baseline after assuming zero correlation between adoption rate and expected yield change. Intuitively, it makes sense to assume a positive correlation between expected yield change and maximum adoption. Empirically, however, this correlation didn't have a significant effect on benefits because the probability distribution of expected yield change is symmetric.[12] This is largely a result of modeling yield and adoption as a joint distribution.[13] More robust results might be obtained if the relationship were modeled as a functional one with adoption as a function of yield. However, the results would not be likely to change if a more functional relationship were used, as we draw from relatively narrow intervals of yield change and adoption rate (with min and max values). For instance, for the cold-tolerance trait (an abiotic trait) in Alberta we draw from yield change intervals of 23–30% and adoption rates of 80–90%.

In the case of the NUE trait, when the probability distribution of maximum adoption is changed from the baseline (uniform distribution) to a truncated normal distribution, the average benefits change slightly from C$2748.18 million to C$1749.52 million. Additionally, average benefits changed from C$2748.18 million to C$2736.93 million with a change in the correlation coefficient from the baseline value ($\rho = 0.8$) to zero correlation. Similar insensitiveness of average benefits to the adoption rate distribution and correlation coefficient were noticed for other traits, as shown in table 14.

## Summary and Conclusions

The *ex ante* impacts of novel traits in canola were evaluated using a stochastic economic surplus model. From a Canadian perspective, traits enhancing nitrogen-use efficiency, water-use efficiency, flea-beetle resistance, cold/freeze tolerance, and drought tolerance are likely to generate significant economic benefits. Heat-blast resistance and seed-size improvement were also economically important. Magnitudes of economic impacts varied significantly across Canada's three most important canola-growing provinces because of differences in area under production and intensity of biotic, abiotic, and other stresses across the provinces. For the majority of the traits, the major beneficiaries of the surplus economic benefits generated are Canadian producers, Canadian innovators, and ROW consumers. ROW producers will see a net loss, however. The surplus benefits were sensitive to supply elasticity of canola in Canada, but the benefits were relatively insensitive to demand elasticities. The benefits were moderately sensitive to R&D lags. When adoption rate and yield change are modeled as joint distribution, the benefits are insensitive to the correlation coefficient between the two.

In attempting to identify those traits that yield the highest economic benefit, this study has implications for the direction of future research efforts on canola. For example, higher demand for biodiesel in the future will be met partly though greater production of canola, so breeding for traits that are likely to increase canola productivity can meet the demand for biofuel feedstock in a way that does not raise canola prices.

Since we only considered the impact of yield-increasing, damage-abating, and cost-reducing producer traits in canola, future *ex ante* impact assessments should evaluate qualitative consumer traits, such as improvement in oil flavor and fatty acid profile. However, the evaluation of improved qualitative traits would require a different methodology altogether—one in which consumers would be surveyed in a contingent-valuation framework—to ascertain how much they are willing to pay for a desired quality trait in canola.

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[12] The mean of the random numbers drawn from a symmetric probability distribution function (PDF) will approach the midpoint of the distribution. Since we are assuming a high correlation (0.8) between yield change and adoption, a "randomly selected" larger (smaller) number for expected yield change from its PDF will call for a larger (smaller) number to be selected from probability distribution of maximum adoption. So the mean of numbers drawn from a PDF of adoption will also approach its midpoint. On the other hand, if we assume no correlation between yield change and adoption, the yield change and adoption will be chosen at random from their independent PDFs, and the mean of the numbers drawn from these PDFs will again reach the midpoint of the distributions. In case the distribution of yield change is asymmetric, the mean of the number drawn from PDFs of yield change and adoption parameters will be away from the midpoint in the presence of strong correlation between the parameters. If there is no correlation, only the mean of the PDF of yield change will be away from the midpoint of the distribution. Thus, the impact would differ with the degree of correlation when the PDF of yield change is asymmetric.

[13] We thank an anonymous reviewer for this observation.

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## Appendix A: Canola Traits Identified as Potentially Valuable for Canada

**Table A1.**

| Serial no. | Trait | Serial no. | Trait |
|---|---|---|---|
| 1. | Nitrogen-use efficiency | 22. | Alfalfa-looper resistance |
| 2. | Water-use efficiency | 23. | Beet-webworm resistance |
| 3. | Herbicide tolerance | 24. | Bertha-armyworm resistance |
| 4. | Drought tolerance | 25. | Diamond-back moth resistance |
| 5. | Cold/freeze tolerance | 26. | Lygus-bug resistance |
| 6. | Heat-blast resistance | 27. | Red-turnip resistance |
| 7. | Lodging resistance | 28. | Beetle resistance |
| 8. | Pod-shattering resistance | 29. | Root-maggot resistance |
| 9. | Soil-salinity resistance | 30. | Sclerotina stem rot resistance |
| 10. | Soil-acidity tolerance | 31. | Clubroot resistance |
| 11. | Solontezic-soils tolerance | 32. | Blackleg resistance |
| 12. | Early maturity | 33. | Alternaria resistance |
| 13. | Early seeding/sowing | 34. | Brown-girdling-root-rot resistance |
| 14. | Oil content | 35. | Staghead resistance |
| 15. | Fatty-acids profile (oil) | 36. | Number of plants per unit area |
| 16. | High-protein content (meal) | 37. | Number of branches per plant |
| 17. | Green-seed elimination | 38. | Number of pods per branch |
| 18. | Flea-beetle resistance | 39. | Number of seeds per pod |
| 19. | Cutworm (pale-western) resistance | 40. | Seed size |
| 20. | Clover-cutworm resistance | 41. | Leaf-area index |
| 21. | Cabbage-seed-pod-weevil resistance | | |

*Source:* (Canola Council of Canada, 2012)

## Appendix B: Detailed Calculation for Gross Discounted Surplus Benefits (Millions C$) for the Case of Cold Tolerance Trait

| Year | % Supply Shift ($K_t$) | % Price Reduction ($Z_t$) | Producer Gains from Adoption | Producer Losses from Price Reduction | Producer Surplus Canada [4+ 5] | Consumer Surplus Canada | Producer Losses ROW | Consumer Gains ROW | Gross Surplus Benefits [6+7+8+9] |
|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| 2021 | 1.138 | −0.288 | 40.398 | −8.539 | 31.859 | 3.038 | −27.372 | 36.800 | 44.325 |
| 2022 | 1.432 | −0.363 | 49.142 | −10.387 | 38.754 | 3.846 | −33.278 | 44.748 | 54.070 |
| 2023 | 1.746 | −0.442 | 57.914 | −12.241 | 45.672 | 4.657 | −39.198 | 52.716 | 63.848 |
| 2024 | 2.059 | −0.521 | 66.047 | −13.961 | 52.086 | 5.408 | −44.680 | 60.100 | 72.915 |
| 2025 | 2.353 | −0.596 | 72.961 | −15.422 | 57.539 | 6.047 | −49.335 | 66.372 | 80.622 |
| 2026 | 2.612 | −0.661 | 78.294 | −16.549 | 61.744 | 6.539 | −52.921 | 71.206 | 86.569 |
| 2027 | 2.829 | −0.716 | 81.949 | −17.322 | 64.627 | 6.877 | −55.375 | 74.517 | 90.646 |
| 2028 | 3.825 | −0.968 | 107.269 | −22.673 | 84.596 | 9.213 | −72.367 | 97.435 | 118.877 |
| 2029 | 3.825 | −0.968 | 103.642 | −21.907 | 81.735 | 8.878 | −69.920 | 94.140 | 114.833 |
| 2030 | 3.825 | −0.968 | 100.137 | −21.166 | 78.971 | 8.554 | −67.555 | 90.957 | 110.927 |
| 2031 | 3.825 | −0.968 | 96.751 | −20.450 | 76.301 | 8.241 | −65.271 | 87.881 | 107.152 |
| 2032 | 2.869 | −0.726 | 70.003 | −14.796 | 55.207 | 5.771 | −47.288 | 63.637 | 77.326 |
| 2033 | 1.913 | −0.484 | 45.028 | −9.517 | 35.511 | 3.464 | −30.458 | 40.966 | 49.483 |
| 2034 | 0.957 | −0.242 | 21.734 | −4.594 | 17.140 | 1.311 | −14.721 | 19.789 | 23.520 |
| 2035 | 0.002 | −0.001 | 0.034 | −0.007 | 0.026 | 0.003 | −0.023 | 0.031 | 0.037 |
| | | *Total* | 991.302 | −209.533 | 781.769 | 81.843 | −669.761 | 901.294 | 1095.150 |

*Notes:* The sum of gross discounted benefits of C$1,095.15 million (sum of last column) and innovator surplus gains of C$473.39 million add up to total global surplus of C$1568.54 million, given for cold-tolerance trait in table 6. The innovator gains are calculated as a product of technology fee, adoption, and canola acreage affected by cold over the time horizon.