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Insight

The Role of Systems Modeling for Sustainable Development Policy Analysis: the Case of Bio-Ethanol

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ABSTRACT. A dynamic systems modeling technique has been developed to assess technologies according to the criterion of sustainability. In a case study, the potential contribution of bio-ethanol toward achieving Canada's commitment to the Kyoto targets for greenhouse gas reductions is analyzed. The analysis concludes that, although bio-ethanol may help reduce greenhouse gas emissions, the technology by itself is insufficient to meet the Kyoto target. Applying the systems modeling approach to analyze sustainability helps highlight those policy issues that warrant more in-depth study. Although the systems model may not provide definitive answers, it raises relevant questions about physical constraints that might be encountered and estimates the extent to which sustainability targets may be met under various scenarios.

INTRODUCTION

Scientific input often plays a key role in matters of public policy, particularly those areas concerned with the impact of human activities on the environment. Scientific knowledge is called for not only in the design of effective problem-solving policies, but also in the identification of the problem itself. Dynamic systems modeling is a scientific approach in which the objective is the synthesis of scientific understanding in such a way that it can be brought to bear on issues of public policy, such as climate change and sustainable development.

The term "sustainability" achieved popular currency in the Brundtland Report (WCED 1987), which links environmental protection to global development and emphasizes the responsibility humankind has for future generations. The report defines sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This definition stresses intergenerational equality that requires a dynamic balance between maintenance ("sustainability") and transformation ("development"). Although a high moral goal is presented, there is little guidance about how to achieve it.

One approach calls for policy makers to use sustainable development indicators (Mitchell 1996) to properly understand and make use of available data on social, economic, and physical environments when making decisions. There are numerous initiatives around the world attempting to develop the most appropriate set of sustainability indicators (National Round Table on the Environment and the Economy 2003, Department of Trade and Industry 2000). One finding suggests that each region or community should define its own set of indicators to reflect its own circumstances (Department of Trade and Industry 2000).

Another related approach is that of "The Natural Step" (TNS), an international non-profit organization that uses a science-based systems framework to help organizations, communities, and individuals take steps toward sustainability (Robert et al. 1997). A planning methodology called backcasting is used, whereby an envisioned desirable future outcome forms the basis for designing strategic paths in a complex system in which current trends, actions, and infrastructures could all be contributors to, or underlying causes of, unsustainability (Holmberg and Robert 2000).

Instruments such as laws and regulations, international treaties, taxes, subsidies, expenditure programs, and

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incentives all have an impact on sustainable development. Policies need to be designed with full consideration of their impact on the following three aspects: economic efficiency, environmental integrity, and people's well-being. Because the issues are complex and interwoven, there are usually strong political complications that make systemic change very difficult. The challenge goes beyond developing strategies for achieving sustainable development to actually implementing them in the real world. Changing people's behavior can be a daunting task. The field of psychology can help by conceptualizing the socio-behavioral aspect of environmental degradation from the perspective of driving forces, such as population, consumption, and technology, by assessing human "quality of life," and by envisioning "what would a sustainable world look like?" (Schmuck and Vlek 2003).

The international community has responded to the ecological challenge of sustainable development. In 1987, with the issue of the Montreal Protocol on substances that deplete the ozone layer, 37 signatory nations agreed to cut by half their release of chlorofluorocarbons (CFCs) into the environment by the year 2000. The 1992 Rio Earth Summit highlighted the potential risks to the environment and long-term economic and social development created by current patterns of industrialization, population growth, and social inequality. In 1997, over 150 countries negotiated the Kyoto Protocol, which requires nations to cut their emissions of greenhouse gases substantially in the coming years. These advances are having an impact on businesses. It is becoming more and more evident to corporate leaders that environmental responsibility is the next step in total quality management to ensure the continued competitiveness and profitability of their companies. International business networks, such as the World Business Council for Sustainable Development, promote eco-efficiency, innovation, and corporate social responsibility in the context of sustainable development.

ASSESSING TECHNOLOGIES FOR SUSTAINABILITY

One important role for national research organizations is to assess the contribution that particular technologies applied at a local or regional level might make in reaching the goal of sustainability. These organizations carry out a mix of basic and applied research to support the development of technology that would not otherwise be developed for purely commercial reasons. Researchers can play a role in developing methodologies that can be used to operationalize the guiding principles of sustainability, giving reliable results as a basis for policy decisions within the various segments of society, such as industry, government, consumers, etc. What is needed from a methodological point of view are assessment methods that distinguish between developments that are more-or-less sustainable, and those that are definitely unsustainable.

These research organizations must make choices among technologies according to explicit criteria. Traditionally, the main criterion for making these choices was economic efficiency. A new technology was worth pursuing if it led to lower-cost products and services. Cost–benefit analysis was the main tool used for technology assessment. The scope of the analysis tended to be restricted to the targeted technology.

By the 1960s, it became clear that pollution abatement or the reduction of environmental impact was an important criterion to be used in technology assessment along with cost reduction. Once pollution reduction was accepted as a criterion, the systems boundary of the analysis had to be enlarged to incorporate more and more upstream and downstream processes. It was recognized that pollutants might be reduced in the targeted process, but sometimes only at the cost of increasing pollutants in upstream or downstream processes. For example, emissions at the tailpipe can be reduced using hydrogen-fueled engines, but the reduction at the tailpipe may be partially offset or even exceeded by emissions from the processes involved in the production of the hydrogen. A life-cycle view needs to be adopted to assess technologies from the perspective of environmental impact (SETAC 1990).

Environmental impact analysis and life-cycle assessment methods rely on comparative analysis. Essentially, it was sufficient to show that a new technology had the potential to be "better"—in terms of economic performance and environmental impact on a per unit basis—than the technology it was to supplant, in order to warrant support for its development.

It is now conventional wisdom in the years following the publication of the Brundtland Report that the "sustainable development" objective must be achieved if future generations of humankind are to have access to an endowment of natural capital as rich as that available to the current generation. Thus, it has become necessary to include sustainability as a third criterion for assessing new technologies. However, the partial comparative methods that have been used for conventional technology assessment are inadequate for analyzing sustainability for several reasons.

First, sustainability is a concept that is comprehensive in that it is a property that applies to a system as whole, just as "temperature" and "pressure" are properties that apply to a gas, not to the individual molecules that constitute the gas. Second, the concept of sustainability is anchored in time; it has a clear reference to the future in that it is concerned with the persistence of harmonious relationships between human activities and the environment over a finite time horizon into the future. Third, sustainability implies finiteness and limits to growth when growth is conventionally defined as increasing in magnitude. Consequently, sustainability is a property that might be ascribed to a future trajectory of a whole system to a relatively long but arbitrarily finite time horizon.

Ideally, the technologies to be assessed need to be embedded as part of a whole system in such a way that the evolution of the system over the long term can be simulated with and without penetration of the targeted technology. It is not sufficient to know that a new technology is better than the technology that it is intended to displace; it is also necessary to determine the extent to which the technology must penetrate if it is to deliver the property of sustainability. The possibility arises that the choice of a better technology may preclude the technology that can deliver the property of sustainability.

However, it is clearly not practical or feasible to model the "whole" system of which the technology of interest is a part; it will be necessary to explicitly establish a system boundary and keep track over time of the flows across the boundary. It will be desirable to include within the boundary elements that reflect the limitations imposed by the finiteness of the planet—the extent of the sources of materials, energy, labor, and land needed by the technology and the other demands placed on those sources; the extent of the sinks for wastes produced by the technology and the competing uses of those sinks; and the extent of the market for the products of the technology. The system boundary is arbitrary and may be expanded as the analysis proceeds.

In Shi (2002), a general framework for assessment of sustainable development is presented that includes these characteristics: (1) integrate the concerns of society, economy, and ecology; (2) reflect the dynamic aspect in the assessment; (3) delineate the border between sustainability and unsustainability, which may be manifested through a gradual change or a sudden collapse; and (4) provide guidance for decision making and remedial actions.
For a specific assessment model, the following characteristics can be added:

- The time horizon of the model should be sufficiently long to see beyond the short-term cyclical behavior of the system and to see when the constraints imposed by the extent of the sources and sinks come into play.
- The model must be capable of generating alternative scenarios or future trajectories and of identifying tensions or challenges that must be resolved by new technologies or policies if a particular scenario, deemed to be the most attractive, is to be achieved.
- Indicators of sustainability for the system must be identified that can be associated with each scenario. It may be the case that no scenarios can be found that meet the criterion of sustainability, or it may be the case that many scenarios meet it. The model need not determine which scenario is "best" insofar as the weights attached to each indicator are apt to differ among interested parties.
- The model should be capable of generating scenarios depicting the penetration of technologies other than the extant technology and targeted technology, as the choice of one technology may preclude the use of another.

The purpose of the bio-ethanol study carried out at the National Research Council of Canada was to explore the use of dynamic systems modeling techniques for assessing technologies with respect to the criterion of sustainability.

DYNAMIC SYSTEMS MODELING AND SUSTAINABILITY

Simulators are descriptions of complex systems representing the interrelationships among the processes that constitute the system; they combine observations of past states of the system with scientific understanding of processes. As such, simulators are explicit and communicable representations of the mental models that guide human perceptions and actions. Unlike verbal or mathematical descriptions of systems, simulators are active and can be experienced. Learning how the system works arises from the experience of using the simulator. The user will come to appreciate the complex system-as-a-whole behavior as it emerges out of dynamic interactions among relatively well-understood processes.

Thus, simulators are primarily learning devices that extend human powers of perception; they cannot predict what will happen nor can they prescribe what should happen. Just as flight simulators support learning how an aircraft responds to the controls, systems simulators may be used to explore the responsiveness of systems to potential societal actions involving, for example, population growth, life-style, and technology innovation.

The dynamic systems modeling approach developed for assessing sustainability of technologies has the following characteristics:

1. In general, the systems model must take the present state of the system as its starting point and be capable of generating possible future trajectories of the system, subject to time-dependent control variables that control the penetration of new technologies into the system.
2. The model is concerned with answering the question “Where can the system go, if a specified technology is deployed?” It is not, however, concerned with the following questions: “Where will the system go? Where should the system go? What policies have to be put in place to make the system track a particular trajectory?”
3. To answer the question in (2), the model must focus on what is physically feasible; it must be a model of a physical economy focusing on the representation of physical transformation processes and on physical stocks and flows. An example is the Australian Stocks and Flows Framework (Turner and Poldy 2001, Foran and Poldy 2002). In short, the model must abide by the laws of physical science.
4. The physical economy is subject to human volition or control. Control is exercised and coordinated by institutions, governments, private enterprises, families, and individuals, who exchange information through contracts and price signals. As the concern is with answering the question of where the system can go, there is no need for the model to represent the behavior of the controller.
5. The aim of the model is physical coherence, not causality. Feedback in these systems is accomplished by means of, or through, the controller. As the controller is not represented, feedback is not to be expected. In exercising the model, the user acts as the external feedback mechanism. Depending on the outcome of simulating a particular scenario, the user devises additional scenarios for investigation based on his or her objective and intuition. Sensitivity analysis is also facilitated.
6. Processes are independently controlled; the whole system, if it is to be controllable at all, must be over-determined in terms of the control variables. This means that there may be settings of the control variables that are incoherent, which leads to “tension.” In these models, it has been found to be useful to allow for the possibility of tension between the requirements for feedstocks and the availability of those feedstocks. A tension manifested by insufficient availability to meet requirements is an indicator of unsustainability.

THE BIO-ETHANOL CASE STUDY

Context

As the global energy supply continually advances in response to the changing needs of industry and consumers, countries are beginning to address the reality of the need to exploit more sustainable energy sources. Growing international concern about the threat of climate change is increasing the momentum behind the search for ways to mitigate this potentially devastating phenomenon. Policy makers around the globe are seeking the most effective methods for reducing the buildup of greenhouse gases (GHG). As carbon dioxide (CO_2) is the most prevalent GHG, it is the major focus of domestic and international strategies for controlling GHG emissions. The politics of environmental protection is leading governments to initiate programs to reduce carbon emissions, improve energy efficiency, and exploit less carbon-intensive energy sources. Bioenergy is often considered to play a key role amongst these changes, as it is thought that renewable carbon fuel has the potential to address the full range of energy markets, including heat, electricity, and transportation. This conclusion is based on life-cycle analyses such as in Levelton Engineering Limited (1999).

Many developed economies in Europe and North America are investing heavily in the research and development needed to underpin the transition toward renewable forms of energy, including biomass fuels, for the strategic reason that biomass-based energy sources are potentially carbon neutral. For example, bio-ethanol can be produced from waste biomass by converting cellulose into sugar using steam and enzymes. It can be argued that when fiber-based ethanol is burned as fuel, it simply recycles CO_2 back into the atmosphere and does not produce more CO_2 than nature can use, thus having a neutral effect with respect to GHG emissions.

Biomass feedstocks are any plant or animal matter that may be used directly or indirectly as a fuel. In practice, these fall into two main categories: by-product biomass resources arising from other activities (e.g., wood residues, recovered wood waste, straw, forestry residues, etc), and dedicated biomass resources and energy crops grown specifically for fuel, e.g., short-rotation crops and herbaceous grasses. Ethanol is viewed as a usable fuel that can be readily blended with gasoline, used as an octane enhancer, and even as a 85–100% replacement for gasoline with suitable engine modifications.

At present, the cost of producing bio-ethanol is still significantly higher than gasoline before excise and taxes. Thus, the transition to bio-ethanol-blended gasoline will not be based solely on price arguments, but will include a complex suite of rationales addressing issues related to new industries associated with bio-ethanol manufacturing, jobs in the agricultural sector, and the potential reduction of fossil-based GHG. The role that strategic public policy can play in achieving sustainability targets through the use of bio-ethanol fuel needs to be judiciously analyzed.

Model Overview

A dynamic systems simulation model has been developed by the National Research Council (NRC) of Canada and Robbert Associates Limited of Ottawa to analyze the sustainability of bio-ethanol use in transportation. It was implemented using *whatIf?*®, a suite of modeling tools developed to support the design, implementation, and use of process-based simulation models, with a particular focus on capturing the system interactions between human activities and the environment. The case study is presented next to illustrate how the dynamic systems modeling technique can play a role in supporting decision making in policy analysis.

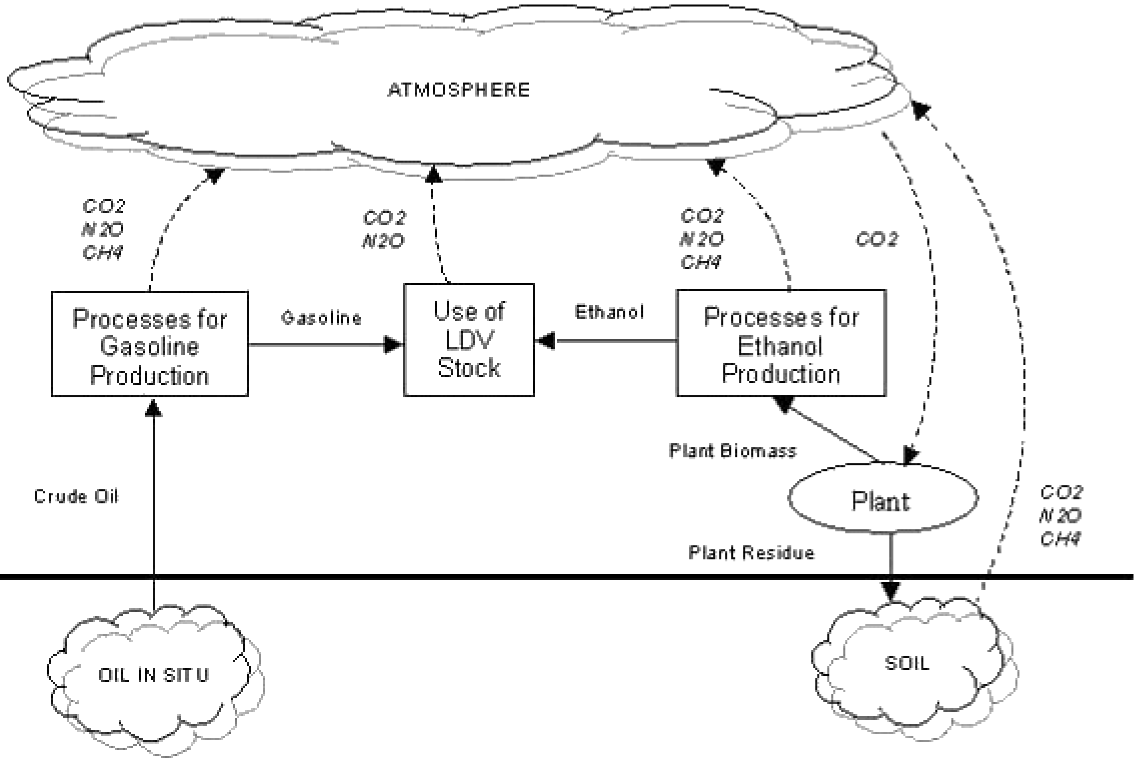
Model structure

The physical flows simulated in the model are shown in Fig. 1.

Figure 2 depicts the high-level compartments of the model.

The fuel consumption compartment keeps track of the stock of light- and heavy-duty road motor vehicles in Canada, their per-vehicle use characteristics, the amount of fuel required to operate the stock, and the tailpipe emissions at the point of use associated with vehicle use. The stock and use of personal-use vehicles are independently related to the number of households in Canada. The stock and use of both heavy- and light-duty commercial-use vehicles are independently related to the Real Domestic Product (RDP, the index that measures production in constant dollars, i.e., discounting the change in prices) of Canada. Both households and RDP are projected independently. The model represents light-duty personal and commercial-use vehicles by three size classes: small passenger vehicles (compact and sub-compact), large passenger vehicles (full size) and light trucks (vans, pick-up trucks, and SUVs). Heavy-duty vehicles are represented in two size classes. Vehicles are also represented by engine type: gasoline engines (capable of using gasoline and 10% ethanol blends), diesel engines, and E85 engines capable of using 85% ethanol blends. Vehicle stocks are vintaged by 31 1-year age classes. Discards from the stock are governed by age and time-specific survivorship probabilities. As new vehicles enter the stock, either to increase the stock or replace discards, they are allocated according to vehicle size and engine type by means of share parameters. In this way, the composition of the stock is determined by the composition of the stock existing at the beginning of the simulation period, the level of stock required, the life tables, and the new vehicle share parameters.

Fig. 1. Physical flows and processes represented in the model. Boxes represent human-designed processes; ellipses represent natural processes; clouds represent sources and sinks; solid lines represent solid/liquid flows; dashed lines represent greenhouse gas flows; LDV means light-duty vehicles.



The fuel production compartment calculates the GHG emissions associated with the production of petroleum-based fuels and of bio-ethanol that may be blended with conventional fuels. It also calculates the emissions associated with the production of the required feedstocks. It keeps track of the emissions associated with resource extraction, including crop production, transport of resource feedstock to the point of fuel production, fuel production, blending, transportation to point of distribution, leaks and flares, and dispensing. Feedstocks can be taken from plant payload production (grains or switchgrass) and/or plant by-product production. The land compartment keeps track of land use for plant production by province (of which there are ten in Canada), transfers of land from potential agricultural land to crop land, carbon content of soil and CO_2 emissions from soil. It also tracks CO_2 emissions from changes in yearly average aboveground biomass. The carbon content of soil is simulated by a linear first order set of difference equations and depends on the starting carbon content for both land types, land transfers, biomass yield for root, support and payload, amount of support incorporated, and the oxidization rate (Bruce et al. 1998).

Model calibration

The time span of the scenarios is 1998 to 2100 with a 1-year time step and, except for the land component, the model was calibrated to track on observed data from 1977 to 1998 in 1-year time steps, supplied by Natural Resources Canada. Observed data for the land compartment were taken from the Agriculture census of Statistics Canada, and the average biomass yields from Agriculture Canada. Oxidation rates were estimated for crop land by assuming that continuous conventional cultivation with the average provincial crop distribution over the long term would result in a soil carbon content of 3%. Potential agricultural land is assumed to have a soil carbon content of 11%. Starting soil carbon content is then estimated by running the land compartment from the beginning of time, which varies by province, until 1997. This results in starting soil carbon contents that vary from 4.6 to 9.6%, depending on the province.

Fig. 2. The bio-ethanol systems model. Solid lines represent information flows; dashed lines represent tracking of GHG emissions.

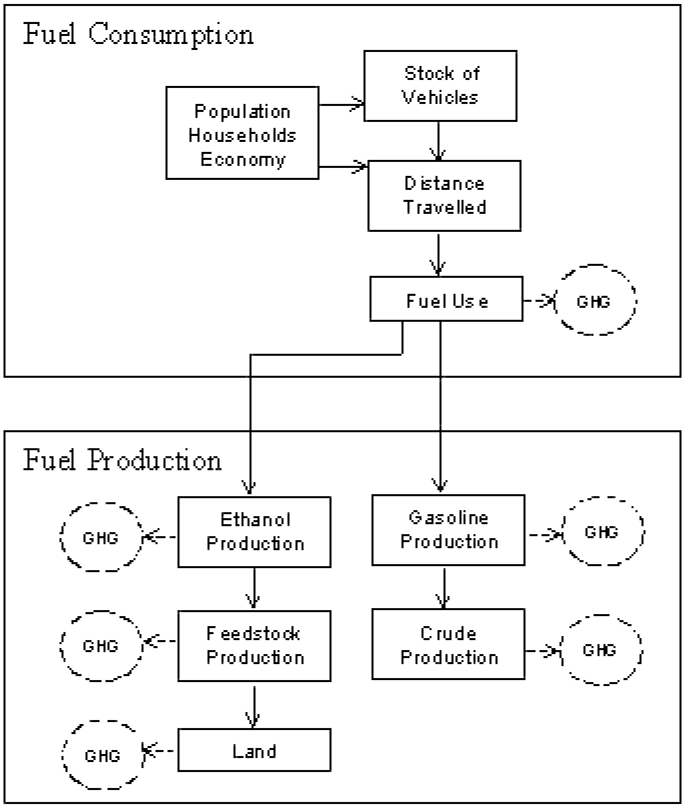
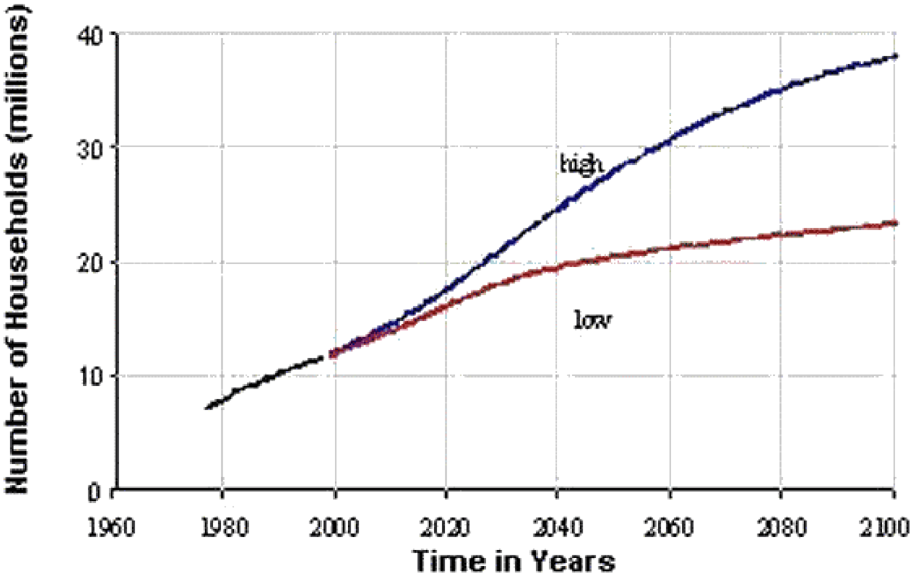


Fig. 3. History and simulated trajectory for number of households in Canada. Black line: history. Blue line: simulated high-growth scenario. Red line: simulated low-growth scenario.



Scenario Analysis

For the purpose of analyzing the impact of the use of bio-ethanol fuels in light-duty vehicle stock in Canada, three scenarios were considered:

Scenario A: Gasoline—All light-duty vehicles are powered with gasoline.

Scenario B: Ethanol—All new light-duty vehicles are powered with E85 engines by 2011, with phase-in beginning in 2001. All light-duty vehicles with gasoline engines use the 10% ethanol blended (E10) fuel by 2011, again with phase-in beginning in 2001. This scenario is intended to represent a rapid and complete penetration of the use of bio-ethanol in Canada.

Scenario C: Ethanol Plus Size Reduction—All personal-use vehicles are fueled as in Scenario B. The trend toward the use of light trucks as personal-use vehicles is reversed in favor of small cars. This scenario is intended to examine the importance of vehicle size relative to the maximal use of bio-ethanol in attempting to meet GHG emissions targets.

To facilitate comparison, all three scenarios are based on the following common assumptions for the number of households in Canada, RDP for Canada, and the amount of service (measured in vehicle-kilometers) delivered by both the personal and commercial-use vehicle stocks.

1. Figure 3 shows the growth in the number of households in Canada. The “high”-growth future corresponds to historical trends in fertility, mortality, and emigration. Immigration is assumed at 1% of population. The “low”-growth future is the same as the high-growth one, except that immigration is held fixed at the last historical period average (200 000 per year). In Scenarios A, B, and C, the low-growth future for households is assumed. It should be noted that GHG emissions are sensitive to growth rates of population and households, and that their most important determinant is immigration.
2. Figure 4 shows the RDP for Canada.
3. Figure 5 shows personal-use vehicle service (distance traveled) measured in vehicle kilometers per year per household.
4. Figure 6 shows light-duty commercial vehicle service (distance traveled) measured in vehicle kilometers per year per dollar RDP.
5. Figure 7 shows the total light-duty vehicle stock.

Under these assumptions, Fig. 7 shows that the stock of light-duty vehicles will double by the year 2100 for all scenarios.

Simulation Runs and Results

Composition of the stock of light-duty vehicles

Figure 8 shows the composition of light-duty vehicle stock as defined in Scenarios B and C.

The composition of the vehicle stock in terms of vehicle size is shown in Fig. 9 for Scenarios A and B, and in Fig. 10 for Scenario C. In Scenarios A and B, the trend in vehicle size class for light-duty vehicle stocks is continued with some saturation. The dominant feature of this trajectory is the rising level of light trucks, which is shown as continuing into the future, although both small and large cars level out. In Scenario C, the vehicle stock is dominated by small cars.

Fuel use in the stock of light-duty vehicles

Use of gasoline and ethanol for all three scenarios is shown in Fig. 11. Scenario A is all gasoline. Scenarios B and C both require gasoline, as the E85-engine fuel is a blend of 85% ethanol and 15% gasoline. The difference between Scenarios B and C reflects the amount of fuel saved by switching to smaller vehicles.

Greenhouse gas emissions

The total net GHG emissions are shown in Fig. 12 for all three scenarios. This total shows only the emissions from flow-based activities. It excludes GHGs emitted directly from agricultural soils as a consequence of cultivation activities. For reference purposes, Fig. 12 shows the Canadian Kyoto target (calculated as 6% below the 1988–1992 average). In all scenarios, the upward pressure on emissions due to the assumed growth of the economy is evident. The dramatic substitution of ethanol fuel in the light-duty stock fuel use for Scenario B meets the target, but the size effect of the economy eventually dominates and drives the total emissions above the target by 2040. In Scenario C, the substitution of small cars for light trucks (a vehicle size substitution effect) delays this cross-over until 2100.

Fig. 4. History and simulated trajectory for real domestic product for Canada. Black line: history. Red line: simulated low-growth scenario.

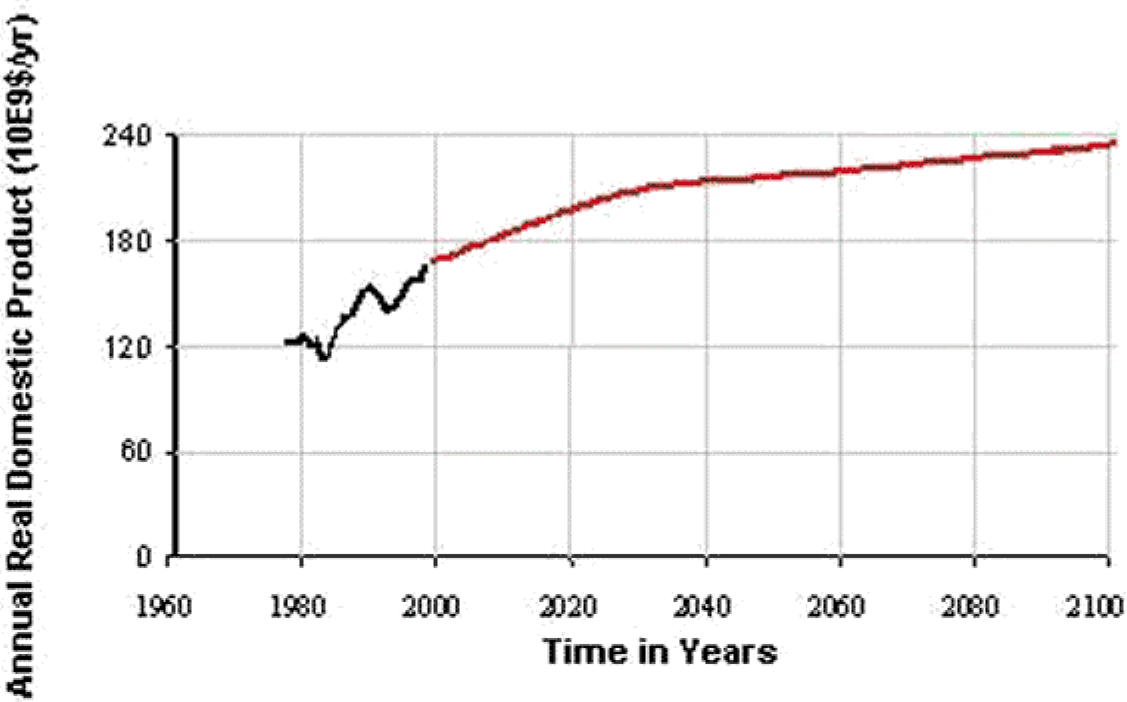


Fig. 5. History and simulated trajectory for personal-use vehicle service, represented by light-duty vehicle distance traveled per household. Black line: history. Red line: simulated low-growth scenario.

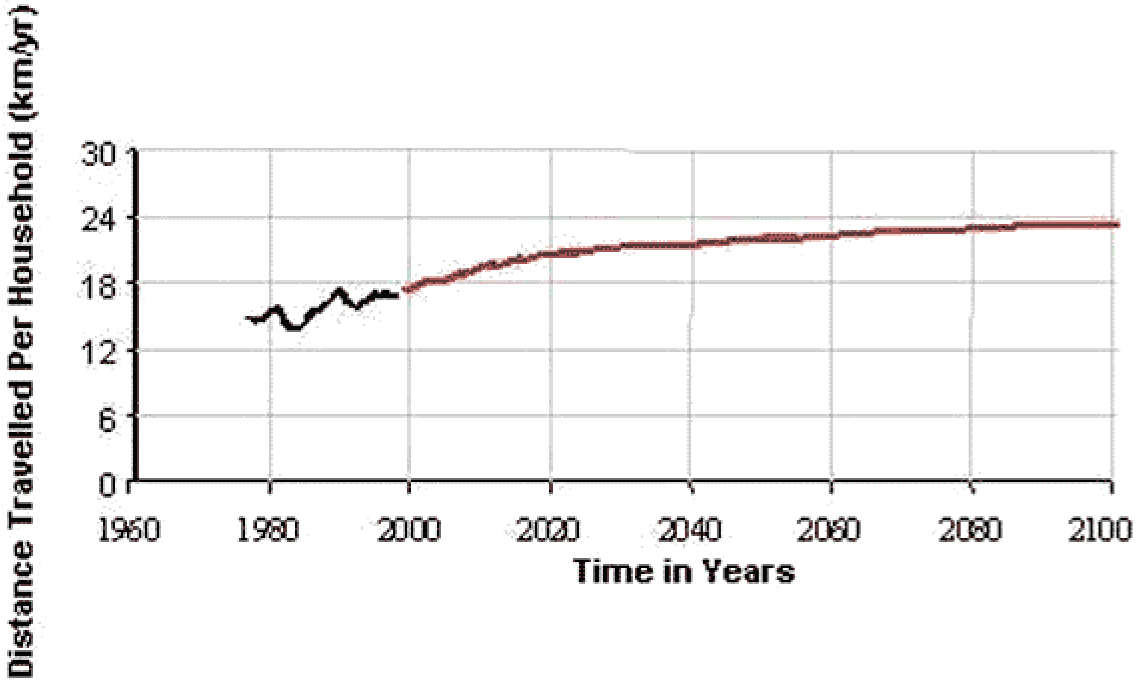


Fig. 6. History and simulated trajectory for commercial vehicle service, represented by light-duty vehicle distance traveled per dollar RDP. Black line: history. Red line: simulated low-growth scenario.

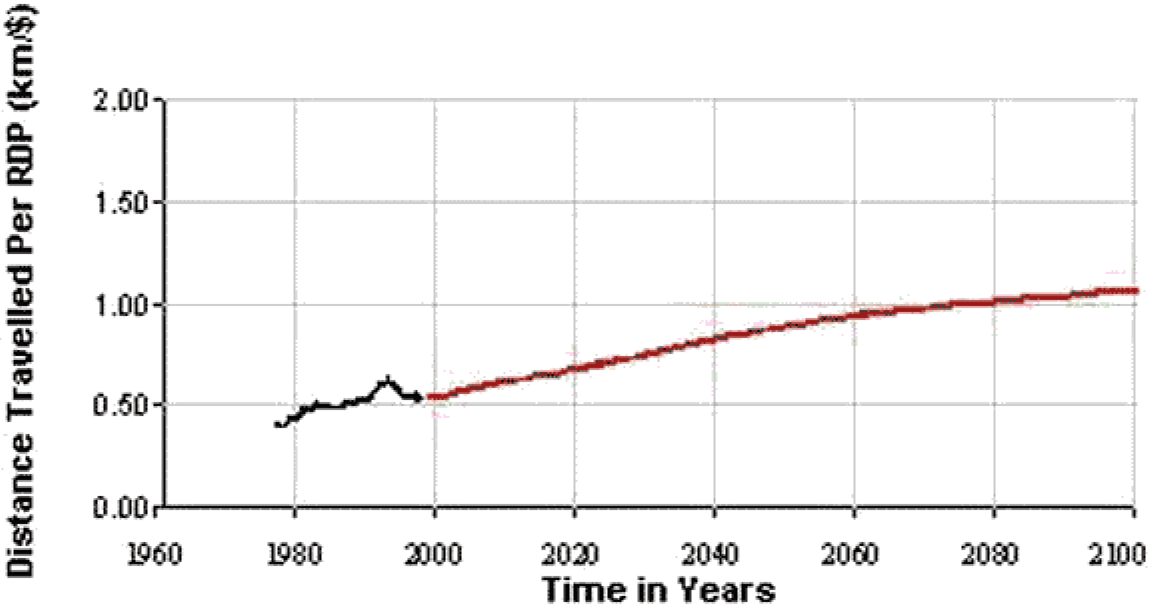


Fig. 7. History and simulated trajectory for total (personal-use and commercial) light-duty vehicle stock. Black line: history. Red line: simulated low-growth scenario.

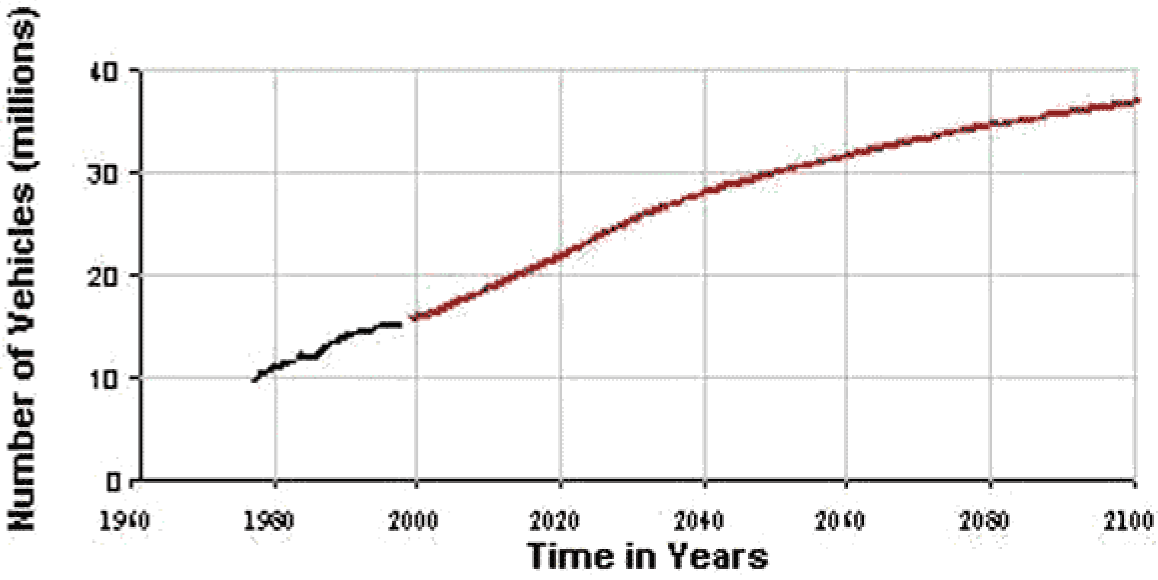


Fig. 8. History and simulated trajectory for light-duty vehicle engine type. The two graphs together show the substitution of gasoline engines by E85 engines. (Please refer to text for explanation of applicable scenarios.)

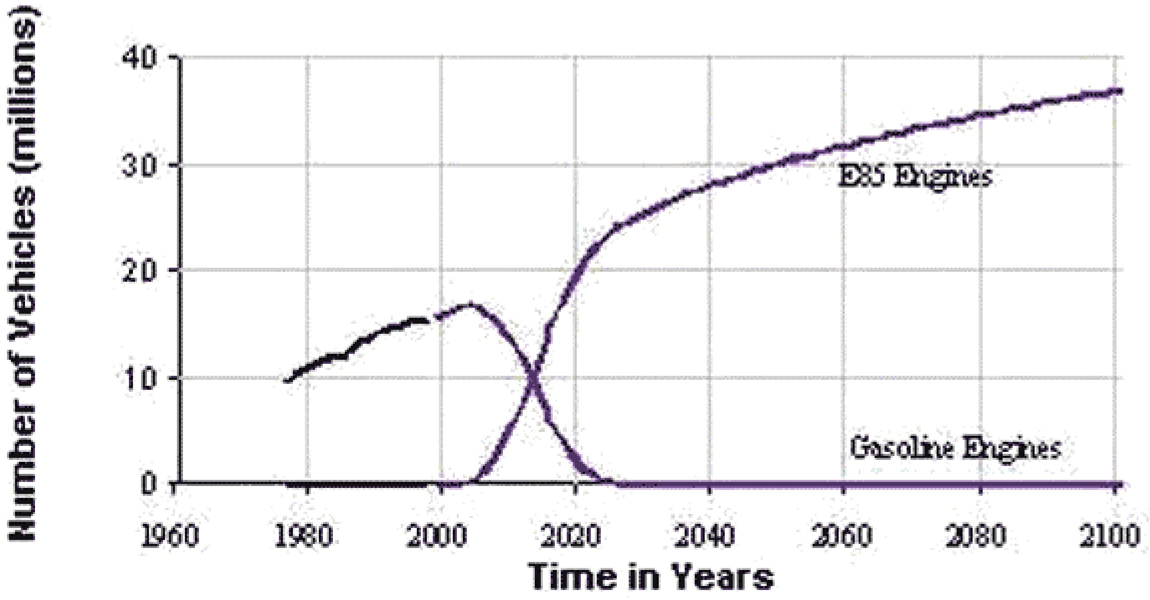


Fig. 9. History and simulated trajectory for light-duty vehicle stock by vehicle size. (Please refer to text for explanation of applicable scenarios.)

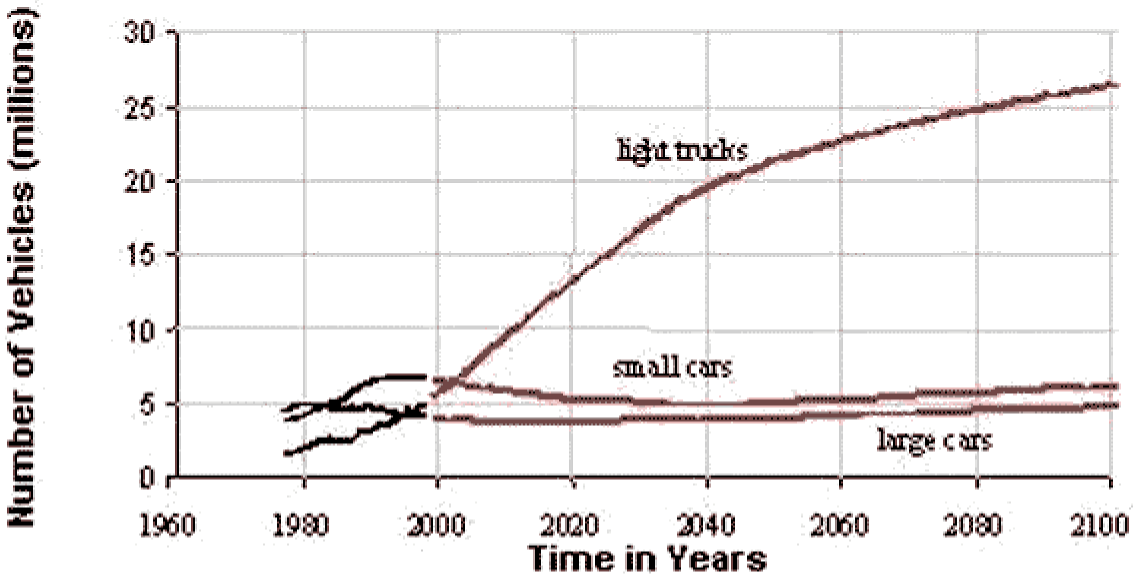


Fig. 10. History and simulated trajectory for light-duty vehicle stock by vehicle size. (Please refer to text for explanation of applicable scenario.)

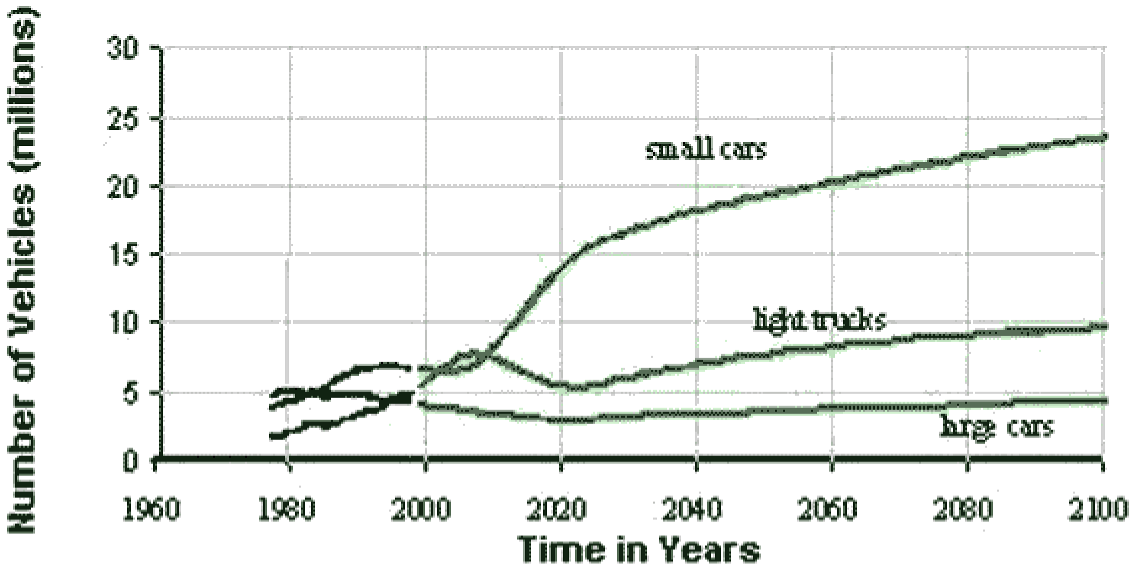


Fig. 11. History and simulated trajectory for gasoline and ethanol use in light-duty vehicle stock. Solid lines: gasoline. Dashed lines: ethanol. (Please refer to text for explanation of applicable scenarios.)

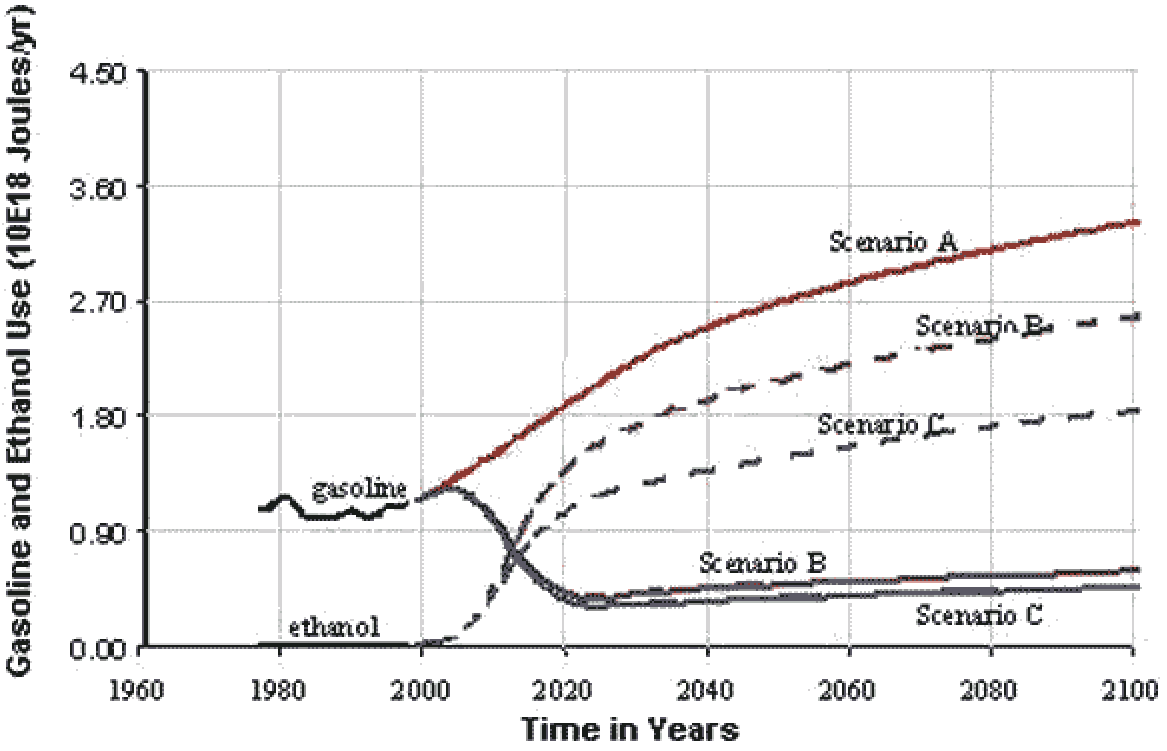
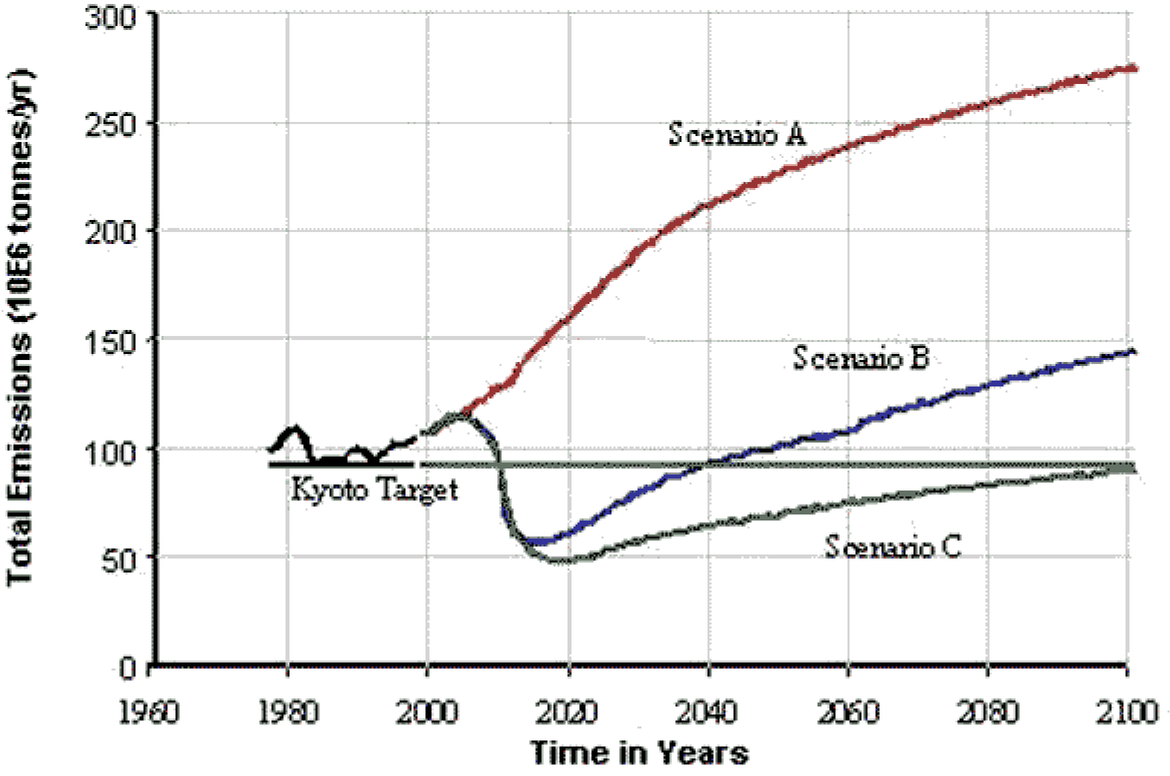


Fig. 12. History and simulated trajectory for total (all sectors) bio-fuel-credit-adjusted GHG emissions in CO_2 equivalent; three variations of low-growth scenario. Scenario A: all gasoline. Scenario B: ethanol. Scenario C: ethanol plus vehicle size reduction.



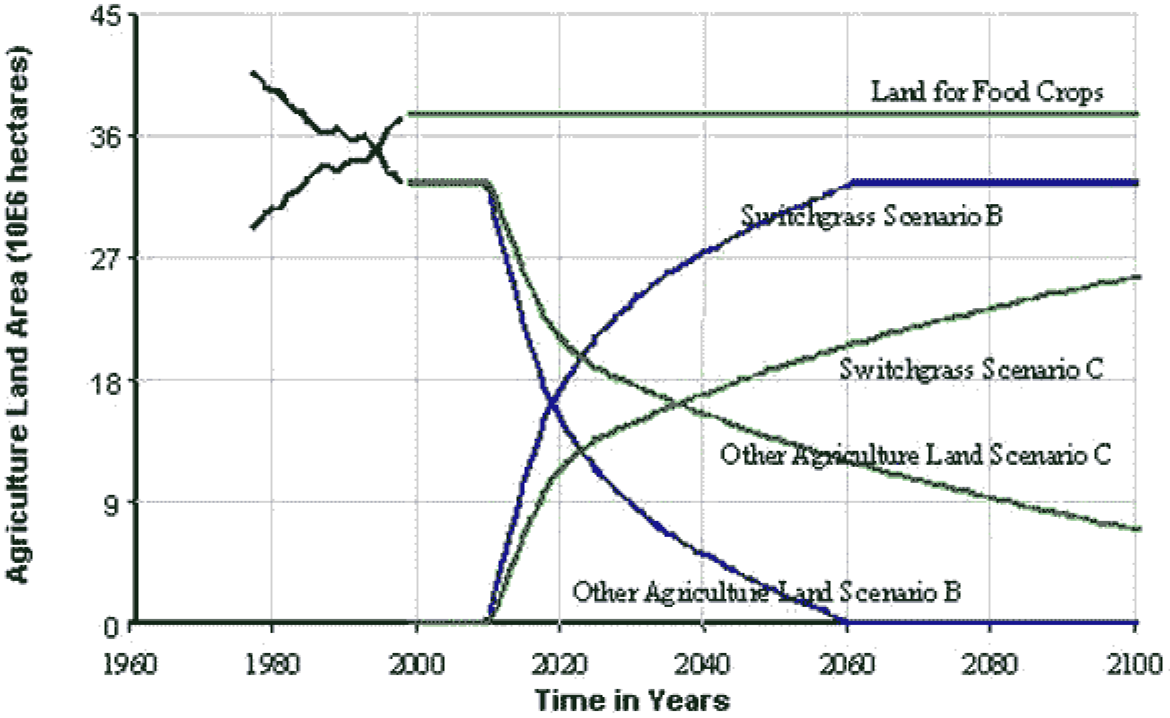
Carbon transfers from agricultural soil to the atmosphere

Carbon in agricultural soils is a significant stock and is affected by human activities. The fundamental determinants of the soil carbon stock over time (and thus emissions) are the initial soil concentrations, the rate of growth of the root mass of the plants on the land, and the oxidation rate (Bruce et al. 1998). Both the root mass growth rate and oxidation rate can be affected by human activities. However, the effects are conditional on the initial state of the soil, are spread over time, and are subject to saturation. On the one hand, virgin soils brought into cultivation for the purpose of growing feedstocks for biofuels are apt to suffer reductions in organic carbon content. On the other hand, soil that has been depleted of carbon may be enhanced with respect to carbon content by human activities, such as no-tillage cultivation and the choice of particular crop rotations. The calculation of this flow depends on the starting condition of the soil, and this measurement is problematic. It is clear that these calculations require a dynamic systems model that is historically bound. Comparative life-cycle calculations that abstract from context are inherently incapable of capturing this phenomenon in a meaningful way. This is a case where it is inappropriate to specify the GHG target as a flow. It should perhaps be specified in terms of a stock—the stock of carbon in agricultural soils. Depending on the starting value of the carbon content of soils dedicated to the production of biomass feedstocks, the rate of transfer of CO_2 from soil to atmosphere (estimated in the computer model) may be as high as 50 million tonnes per year, which is not insignificant when compared with the fossil-based carbon emissions.

Feedstocks for the production of ethanol

Feedstocks for ethanol production in all scenarios come first from crop by-products and then from switchgrass grown on what Statistics Canada terms "other agriculture land," exclusively for ethanol production. Figure 13 shows the use of agricultural land for the production of food and feed crops, agricultural land for producing switchgrass as a feedstock for ethanol production, and other agricultural land (primarily range land for grazing cattle) for Scenarios B and C. Historically, about one half of the agricultural land is used for food and feed crops, and one half is "other agriculture land" that is being transformed into crop land. In Scenario B, there is insufficient feedstock for the production of bio-ethanol after 2060: all crop by-product from land dedicated to food and feed crops in Canada is used for ethanol production and all of the "other agriculture land" is dedicated to growing switchgrass for ethanol production. In Scenario C, about 80% of the other agricultural land is used for growing switchgrass. It is evident from these scenarios that the availability of biomass feedstocks for the production of ethanol will create a dilemma if bio-ethanol is to be widely used to power light-duty vehicles in Canada. It is likely that adequate supplies of biomass feedstocks can only be obtained by reducing food production. This leads to the question of alternative or less land-intensive sources for food for human consumption. The analysis of this issue would require extending the model to include food production and consumption, and the transformation of plant biomass into meat.

Fig. 13. History and simulated trajectory for agricultural land use; two variations of low-growth scenario. Scenario B: ethanol. Scenario C: ethanol plus vehicle size reduction. (Land for food crops same for both scenarios.)



Results from systems analysis

1. The immediate use of ethanol-blended fuel for all existing personal-use and light-duty commercial-use motor vehicles and the introduction and rapid penetration of E85 engines into new personal-use and light-duty commercial-use vehicles together likely would not enable Canada to meet and maintain the Kyoto target for the road vehicle segment of the transportation sector.
2. Furthermore, with no changes in consumer behavior with respect to vehicle size acquisition choice, the introduction and use of bio-ethanol as described above would exhaust the Canadian supply of biomass for the

production of ethanol from crop by-products and "other agriculture land" dedicated to growing switchgrass.

3. A significant change in consumer preference for personal-use vehicles to a point where 80% of new personal-use vehicle sales are small vehicles, in combination with the use of ethanol fuels, as in (1) above, would meet the Kyoto target for 100 years.
4. The potential for biofuels to reduce GHG emissions relative to gasoline hinges on the starting condition of soil carbon content. This is difficult to measure because of regional variations that depend on the cropping history of the soils. In circumstances where virgin soils are brought into cultivation, it is possible that the use of biofuels will generate more GHG emissions than fossil fuels.

UNCOVERING POLICY ISSUES

If an economic system grows 3–5% yearly and that system requires large inputs of fossil and renewable energy to underpin its development, then it follows logically that fossil-fuel use will grow and subsequent emissions of GHGs will also increase. Moving from current patterns of consumption and production to those that are truly sustainable is a major task. The essential change is to effect a planned transition from fossil-based carbon fuels to renewable alternatives. Any set of policies for meeting the Kyoto targets is likely to include those that will increase the efficiency of the vehicle stock as well as those effecting a transition from fossil fuels to non-fossil alternatives, such as electricity or hydrogen produced from non-fossil sources. In short, the solution will involve, along with the introduction of alternative fuels, changes in consumer behavior, whether induced by incentives or mandated by regulations. Although this analysis presumes that the continued use of gasoline will be possible, there is also a need to look at a transition driven by alternatives, such as hydrogen, as the production rates of oil at a global scale are expected to begin to decline within the next decade.

With respect to the potential use of ethanol-based fuels, one of the key questions concerns the source of the biomass. It is clear that sufficient quantities of biomass for the use of bio-ethanol to make a significant contribution to GHG reduction in Canada cannot be obtained without a major reduction in the production of agricultural crops for food. As Canada is an exporter of agricultural crops for food, the issue of trade and alternative sources of foreign currency would arise if Canada were to reduce exports of food crops in order to produce bio-ethanol for domestic consumption. Accordingly, the framework for the analysis of ethanol fuels must be extended to include the food production system so that the trade-offs between the use of land for ethanol production and food production can be examined. As well, technologies for improving the efficiency of land use for food production should be analyzed.

The question of the impact of the removal of crop by-product biomass on soil quality could be important. The large-scale removal of plant residue may reduce the carbon content of soils and increase reliance on amendments to offset the loss in soil fertility. If "other agriculture land" is devoted to the growing of switchgrass as a source of biomass for ethanol production, two questions arise. Is the carbon content of the soil when switchgrass is grown higher or lower than the condition of the soil before switchgrass was introduced? How is "other agriculture land" currently being used? If it is being used for grazing livestock, then alternative sources of livestock feed would become an issue.

Even as it has been projected that the replacement of gasoline with bio-ethanol will lead to a reduction in total life-cycle GHG emissions, this benefit will increase as more Canadian grain is produced using "no tillage" production technology, resulting in increases in soil carbon storage (sequestering) at the expense of atmospheric CO_2. The use of newer technology for crop fertilization, crop handling and storage, and ethanol manufacture will also mean significant reductions in net GHG emissions associated with the production of ethanol from biomass in the years to come.

The simulation model can be exercised to work through a set of scenarios chosen to resonate specific concerns, each illuminating its particular dilemmas involving major components of the system. The base case scenario should not be viewed as a strong prediction. Rather it should be viewed as the basis on which future versions of a physical economy can be molded into a better and more appropriate shape. The significant implication of the scenarios is that the future involves tensions, no matter which path is taken, and there are choices to be made, with strong effects on the behavior of the whole system that require policy intervention. Solutions need to be sought in parallel to resolve interacting dilemmas. Systems modeling helps highlight the key links for policy development.

CONCLUSIONS

A dynamic systems modeling technique has been developed to assess technologies with respect to the criterion of sustainability. In a test case, the potential contribution that the use of bio-ethanol might make toward achieving the goal of Canada's commitment to the Kyoto targets for GHG reductions is analyzed. The analysis concludes that, although the use of bio-ethanol may contribute toward reducing GHG emissions, this technology on its own is insufficient to meet the Kyoto target. As well, the availability of feedstock may become an issue, so that the systems boundary needs to be expanded to encompass, for example, forests as a potential source of biomass, and to address requirements for feed and food, as these compete with fuel biomass for the same land resources. Other fuel alternatives, including fuel cells, ought to be considered in conjunction with biofuels, and the transition to these alternatives needs to be examined as well. In a rush to embrace the environmental benefits of biofuels such as bio-ethanol, it is easy to overlook policy questions that ought to be addressed. Applying the systems modeling approach to analyze sustainability helps bring out those issues that warrant more in-depth study.

Sustainability issues, such as the reduction of total GHG emissions in a growing economy, are complex and intertwined, and require a systems approach to develop a range of solutions. Integrated analysis with a futures focus is often viewed as doubtful and dangerous science, especially when it challenges current policy paradigms. No longer are policy makers confined to analyzing issues such as demography, ecology, and economics in a compartmentalized manner. It is now feasible to perform holistic analyses to yield a deeper understanding for resolving complex dilemmas. At a qualitative level, a wide range of social, economic, and political drivers and future scenarios need to be developed. These can be seen as political options for Canada in the coming decades. At a quantitative level, the national scenarios can be tested for their effect and physical feasibility in a whole-system sense. Simulation runs can be made to help identify tensions that may arise. As users of the model, policy makers can then offer potential solutions whose efficacy can be examined by the model.

Public policies are beginning to reflect the fact that economic strength and environmental stability are interdependent rather than mutually exclusive. High levels of waste and emissions are signs of poor technology, low efficiency, and bad management of resources. Governments that fail to promote efficient environmental management regimes and modern technologies associated with eco-efficiency are engendering a lack of national competitiveness. The importance of including appropriate governance structures and economic incentives in strategies for sustainable development is starting to be recognized. Thus, there is a need for robust methods for the synthesis and communication of understanding of complex systems, so that scientific knowledge can be brought to bear on matters of public policy. Systems modeling techniques, such as the one demonstrated through a sustainability assessment of bio-ethanol, have the potential to provide valuable insight on a given policy issue. Although the systems model may not provide definitive answers, it serves to raise the appropriate questions regarding physical constraints that might be encountered, and can estimate the extent to which sustainability targets may be met under various scenarios, thereby adding a needed scientific dimension to public policy debate.

Responses to this article can be read online at: http://www.ecologyandsociety.org/vol9/iss2/art6/responses/index.html

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