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# Assessing land clearing potential in the Canadian agriculture–forestry interface with a multi-attribute frontier approach

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ABSTRACT

The pattern of forest land clearing in a region can be viewed as a gauge of sustainable (or unsustainable) use of agricultural and forest resources. In this study we examine the geographical distribution of land clearing potential in the Canadian agriculture–forestry interface and propose a new landscape-scale indicator that quantifies this potential. We consider the possibility that forested land will be cleared for agriculture as a trade-off between the land's capacity to support agriculture and its comparative value if it remains forested. However, this trade-off is complicated by the land's susceptibility to fragmentation (and subsequent conversion), which derives from the local pattern of forest, agriculture and other land cover types. We find the locations in the agriculture–forestry interface with the highest land clearing potential by delineating nested multi-attribute frontiers in the dimensions of the land's agricultural capacity, its estimated forest productivity and its fragmentation potential. The multi-attribute frontier concept addresses our lack of knowledge about the relative importance of these multiple drivers of land conversion by objectively combining them into a single-dimensional land clearing pressure metric in a geographical setting. Overall, our approach provides a simple yet informative indicator which reveals the geographical stratification of land clearing pressures across large regions. In general, the spatial delineation of areas with high land clearing potential agrees well with recent evidence of land clearing and deforestation events in Canada.



## 1. Introduction

Land clearing (deforestation) is part of the process of converting forested areas to other land uses. Forests and shrublands have historically been seen as a potential source of agricultural land (Ramankutty and Foley, 1999). In many parts of the world, conversion of forested lands to agriculture is one of the key processes in modern landscape dynamics (Foley et al., 2005; Green et al., 2005; Millennium Ecosystem Assessment, 2005). The potential of forest land to be cleared for agriculture can be seen as a gauge of the degree of sustainable (or unsustainable) use of forested landscapes.

In Canada, deforestation is caused mainly by the conversion of forested lands to agriculture, but also by industrial and urban development, mining and road building (NRCan, 2011). The rate of deforestation in Canada has declined over the last decade (NRCan, 2011) with the annual rate dropping from over 64,000 ha $yr^{-1}$ in 1990 to approximately 44,800 ha $yr^{-1}$ in 2009. Historically, the land area cleared for agriculture and pasture has constituted the largest portion of the annual deforestation footprint, accounting for 65% of total area cleared (41,900 ha) in 1990 and 43% (19,100 ha) in 2009.

Land clearing is a significant source of greenhouse gas (GHG) emissions (Fitzsimmons et al., 2004; Gibbons and Lindenmayer,

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2007; Environment Canada, 2012). In 2010, land clearing activities in Canada resulted in net greenhouse gas (GHG) emissions of 14.8 million tonnes of carbon dioxide equivalent (Environment Canada, 2012). In the long run, land clearing reduces the resilience of ecosystems (Bennett, 1999; Walker and Salt, 2006), leads to an irreversible gradual loss of natural habitats (Cogger et al., 2003) and diminishes the capacity of ecosystems to sustain plant productivity (Green et al., 2005; Millennium Ecosystem Assessment, 2005; Wentworth Group of Concerned Scientists, 2003).

While numerous negative impacts of land clearing have been recognized (Foley et al., 2005; Green et al., 2005), estimating the potential of forested land to be cleared is difficult. Estimating economic triggers that cause land to be converted to agriculture is particularly challenging because landowners' decisions to clear forested woodlots often include subjective motivations which cannot be described in terms of conventional cost-benefit calculations. Landowners often show reluctance when considering projects that involve long-term allocation of land and reveal preferences for short-term projects, which give them more managerial flexibility (Korhonen et al., 2002; Blanco and Forner, 2000), and thus tend to move into activities with short production cycles such as agriculture (Parks, 1995; Parks and Hardie, 1995). Factors that are often omitted in conventional cost-benefit calculations include potential irreversibility in land use change and future uncertain costs associated with maintaining long-term projects versus more certain benefits of short-term projects (Pindyck, 1995). The issue of estimating land clearing potential becomes especially important in forecasting nationwide economic production scenarios in the agricultural and forestry sectors (Horner et al., 1992) because conversions between agricultural production and forestry usually mean long-term land use commitments. The latter aspect has been recognized as a significant concern for many landowners (Stevenson, 2003a,b) and could have serious implications for agricultural and forest sector production capacities.

### 1.1. Estimating the land clearing potential based on land's productivity capacity

Several methodologies have been proposed to quantify land clearing pressures at large geographical scales. One method evaluates risks of habitat degradation and land cover change by analyzing the historical dynamics of forest fragmentation and changes in key landscape mosaic types (Riitters et al., 2009a,b; Riitters and Coulston, 2005; Wickham et al., 2010). Other methods employ statistical and spatial regression techniques for estimating land use change potential (Hobson et al., 2002; Aguiar et al., 2007) by linking historical land use change data acquired from satellite imagery to econometric information (Nelson and Hellerstein, 1995; Vance and Geoghegan, 2002; De Pinto and Nelson, 2007), or by applying various discrete choice models (Fleming, 2004). Other common approaches estimate potential costs associated with the loss of environmental services provided by forest lands after clearing (Barbier, 2007) or future costs of associated greenhouse gas emissions (Kindermann et al., 2008). Some studies have framed the land clearing problem in terms of finding the optimal time to switch away from an existing land use policy (Irwin and Bockstael, 2001; Vance and Geoghegan, 2002).

Many of the aforementioned modelling approaches require considerable amounts of spatially referenced econometric data. This information may not be available for large, sparsely populated regions, such as vast portions of the agriculture–forestry interface in sub-boreal Canada. In such situations, broad-scale assessments based on land's production capacity can be used to limit the geographical extent of future data gathering efforts to areas with high land clearing potential. Fortunately, the information required to assess production capacity at a broad scale can be found in standard land surveys and forest inventories, which – unlike detailed econometric data – are generally available for large, sparsely populated regions.

In this study, we develop a new landscape-scale indicator that evaluates the potential for forested areas to be cleared for agriculture as a trade-off between the areas' capacity to support agricultural production and their productivity if they were to remain forested. Notably, this is not always a straightforward trade-off, since some forested areas may be predisposed towards conversion due to a pattern of expected (or ongoing) landscape fragmentation. Our assessment is focused on forested areas in the Canadian agriculture–forestry interface, a 36-million ha transition zone between semi-boreal forests and the major areas of agricultural production in Canada (Fig. 1). We divide the entire area of the Canadian agriculture–forestry interface into small land parcels (250 m × 250 m map cells) and analyze each parcel in the dimensions of its capacity to support (1) agricultural or (2) forest biomass production, as well as (3) its fragmentation potential, which describes the likelihood of forest conversion based on local land cover pattern. We then approach the estimation of land clearing potential as a multi-criteria ordering problem and find the parcels with the highest clearing pressures via delineation of nested multi-attribute frontiers in the three aforementioned criteria dimensions.

## 2. Methods

### 2.1. Multi-attribute frontier (MAF) concept

Integration of multiple data sources into a single-dimensional metric is often accomplished via multi-criteria decision analysis (MCDA). MCDA involves a variety of approaches, such as listing multiple lines of evidence (King and Richardson, 2003), indexing (Feron et al., 2004), scoring (McDonald et al., 2007) or other statistical methods (Landis, 2003; Linkov et al., 2009). Generally, these methods help determine a preference order among a number of available options (or scenarios) in a multi-dimensional criteria space based on various types of information obtained from a multitude of data sources (Janssen, 1992; Lahdelma et al., 2000; Linkov et al., 2006; Yatsalo et al., 2007).

The assignment of weights to individual criteria is one of the simplest and most popular methods in the MCDA toolset (Linkov et al., 2009, 2011). Linear weighted averaging (LWA) represents one of the most common weighting methods (Steele et al., 2009). For example, when constructing a map composed of $j$ land parcels (or map cells), the criteria – in our case, the capacity of a parcel to support (1) agriculture or (2) forest vegetation as well as its (3) fragmentation potential – may be standardized to scores that are then combined by weighted averaging into a continuous metric:

$$R_j = \sum_{k=1}^{K} Z_{j_k} w_k \qquad (1)$$

where $Z_{j_k}$ is the normalized value of criterion $k$ for element $j$, which falls within a common numeric interval, $[Z_{\min}, Z_{\max}]$, $w_k$ is the normalized weight for criterion $k$ and $K$ is the size of the criteria space ($K = 3$ in our case). Ideally, the weighting coefficients $w_k$ are estimated using exogenous information about their relative importance. However, such knowledge is often incomplete or unavailable and the weights are instead determined through the subjective assessments of experts. Several approaches have been proposed to reduce the biases of experts in this context, such as constructed (Keeney and Raiffa, 1976) or triangulatory (Florig et al., 2001; Morgan et al., 2000) rankings, treatment of experts' beliefs as distributions and their subsequent rankings via stochastic dominance criteria (Andrews et al., 2004; Hadar and Russel, 1969; Levy