

Paving the Way for Invasive Species: Road Type and the Spread of Common Ragweed (*Ambrosia artemisiifolia*)

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Abstract Roads function as prime habitats and corridors for invasive plant species. Yet despite the diversity of road types, there is little research on the influence of these types on the spread of invaders. Common ragweed (*Ambrosia artemisiifolia*), a plant producing large amounts of allergenic pollen, was selected as a species model for examining the impact of road type on the spread of invasive plants. We examined this relationship in an agricultural region of Quebec, Canada. We mapped plant distribution along different road types, and constructed a model of species presence. Common ragweed was found in almost all sampling sites located along regional (97%) and local paved (81%) roads. However, verges of unpaved local roads were rarely (13%) colonized by the plant. A model (53% of variance explained), constructed with only four variables (paved regional roads, paved local roads, recently mown road verges, forest cover), correctly predicted (success rate: 89%) the spatial distribution of common ragweed. Results support the hypothesis that attributes associated with paved roads strongly favour the spread of an opportunistic invasive plant species. Specifically, larger verges and greater disturbance associated with higher traffic volume create propitious conditions for common ragweed. To date, emphasis has been placed on controlling the plant in agricultural fields, even though roadsides are probably a much larger seed source. Strategies for controlling the weed along roads have only focused on major

highways, even though the considerable populations along local roads also contribute to the production of pollen. Management prioritizations developed to control common ragweed are thus questionable.

Keywords Agricultural landscape · *Ambrosia artemisiifolia* · Invasive plant · Mowing · Quebec · Roadside

Introduction

Roads are increasingly considered drivers of major environmental change, not only in regions with dense road networks, but also in more pristine landscapes. Roads may disrupt ecosystem integrity through their construction and existence and also by creating access for further disturbances. For instance, in the United States, 20% of the total land area is within 127 m of a road, and only 3% is more than 5 km away (Riitters and Wickham 2003). In this country, it has been estimated that almost 4.8 million ha of land and water bodies have been destroyed by road construction (Trombulak and Frissell 2000). At least 22% of the land is now ecologically altered by the road network (Forman 2000).

Roads function as prime habitats and corridors for invasive plant species, although their importance has often been neglected in statistical models predicting the spread of plant invaders (Hulme 2003). Roadsides are usually well-drained, open habitats that are frequently disturbed by maintenance activities (vegetation mowing, drainage ditch cleaning). They are also polluted by heavy metals (Trombulak and Frissell 2000), de-icing salts (Kaushal and others 2005; Ramakrishna and Viraraghavan 2005) and fertilizers (Jodoin and others 2008). Although roadsides

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can be colonized by a wide array of native plant species (Rentch and others 2005; Karim and Mallik 2008), their characteristics (open and disturbed) are particularly propitious for the establishment of opportunistic exotic species (Greenberg and others 1997; Gelbard and Belnap 2003; Pauchard and Alaback 2004; Jodoin and others 2008; Kalwij and others 2008).

The role of road type is potentially important for several invasive plants, because paved roads only represent a fraction of the total road network in some countries or regions. For instance, 49 and 42% of Canada's and United States' road networks are made up of gravel roads (Forman and others 2003). In southern Utah, the richness and cover of exotic plant species are much higher along the verges of paved roads than along unpaved roads or four-wheel-drive tracks (Gelbard and Belnap 2003). In Scotland, verges of national roads have more ruderal plant species (some invasive) than those of minor, rural roads (Truscott and others 2005). In southern Quebec, the invasive genotype of the common reed (*Phragmites australis* ssp. *australis*) is 2.6× more common along national roads than along regional or local roads (Lelong and others 2009; LeBlanc and others 2010). Smooth bedstraw (*Galium mollugo*) is 4× more abundant along paved roads than along unpaved roads inside a national park of eastern Quebec (Meunier 2008). The success of exotic species along paved roads has been attributed to higher levels of incident sunlight, greater disturbance due to road maintenance, and larger road verges (Gelbard and Belnap 2003; Truscott and others 2005; Meunier 2008; Lelong and others 2009). On the other hand, in South Africa, a greater diversity of exotic plant species has been found along gravel than tar roads, likely because in this region, gravel roads require more maintenance (more frequently disturbed) than tar roads (Kalwij and others 2008). In the central highlands of India, the difference in species richness of exotic plants along different road types, although significant, is nevertheless extremely small (Sharma and Raghubanshi 2009). There is also little evidence that road type influences the spatial distribution of exotic species along the roads crossing the Mojave Desert (Arizona, Nevada; Craig and others 2010).

Common ragweed (*Ambrosia artemisiifolia*; Asteraceae) was selected as a species model for examining the impact of road type on the spread of invasive plants. Common ragweed is an erect annual herb native to North America that has invaded several regions of the continent where the plant was absent until recently, and some European countries, especially Austria, France, Hungary and Switzerland (Bohren 2006; Chauvel and others 2006; Lavoie and others 2007; Essl and others 2009; Csontos and others 2010). This problematic plant produces large amounts of allergenic pollen (Wopfner and others 2005; Breton and others 2006). The species is also considered an agricultural pest,

especially in vegetable, soybean and sunflower fields (Bassett and Crompton 1975; Cowbrough and others 2003; Saint-Louis and others 2005; Clay and others 2006). There is strong historical evidence that the expansion of road networks has contributed to the spread of common ragweed (Chauvel and others 2006; Lavoie and others 2007; Essl and others 2009; Simard and Benoit 2010). Recent studies suggest that common ragweed populations are first found along roads in newly invaded regions. They also suggest that the hydrological network contributes little to the dispersal of the species (Lavoie and others 2007; Simard and Benoit 2010). However, there are no data on the road types implicated in this spread. Identifying such types is an important issue for the management and control of common ragweed, since it is almost impossible to simultaneously manage (mowing, herbicides, etc.) an entire road network during the pollen production period: control efforts must be more focused.

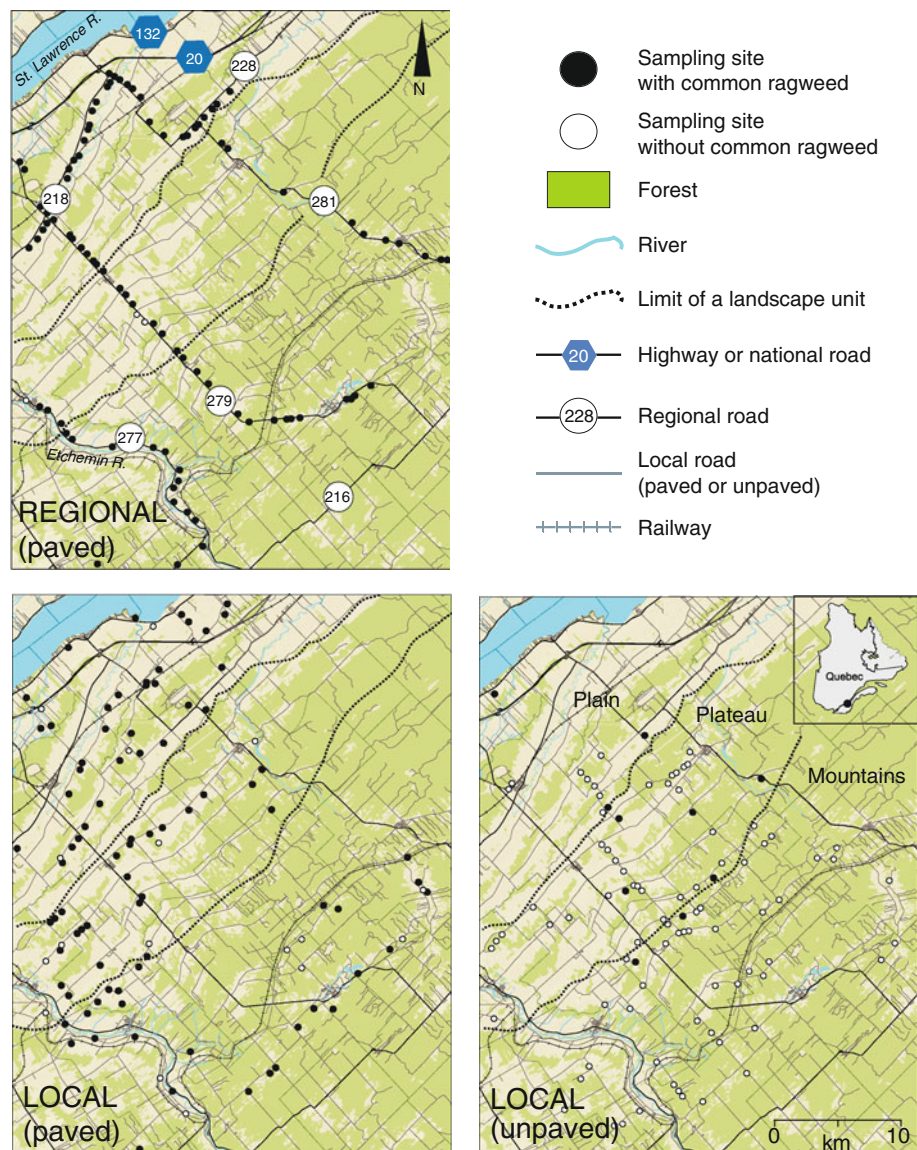
In this study, we examined the impact of road type on the spread of common ragweed in an agricultural region of southern Quebec. We mapped the distribution of the plant along different road types (regional or local, paved or unpaved), and constructed a model of plant presence along roads. We hypothesized that the presence of the invader along roads is mainly influenced by road type, but poorly associated with differences in agricultural use of the lands crossed by roads. We also hypothesized that paved roads, with larger road verges (more habitat space for the plant), and with a higher disturbance level, are more frequently invaded than unpaved roads. Finally, we used the results of the model to evaluate the management strategies currently used by government authorities to control common ragweed.

Methods

Study Area

The spatial distribution of common ragweed along roads was studied in the Bellechasse region (Fig. 1), 32 km southeast of Quebec City, Quebec, Canada (central point: 46°41'N, 70°49'W). This region was selected because of the abundance of common ragweed populations on road verges, and its dense and diverse road network. Its landscape (proportion of agricultural and forested areas, population density) is highly representative of rural areas of the deciduous forest biome of southern Quebec (Robitaille and Saucier 1998). The first common ragweed specimen was collected in the region in 1928 (Lavoie and others 2007). The study area is approximately delineated by the St. Lawrence River (NW), Regional Road 281 (NE), Regional Road 216 (SE) and the Etchemin River (SW), for a total of

Fig. 1 Spatial distribution of the common ragweed (*Ambrosia artemisiifolia*) in the Bellechasse region (Quebec, Canada) along different road types (regional and paved, local and paved, local and unpaved) in September 2009. The limits of the three landscape units of the study area (plain, plateau, mountains) are indicated



1025 km². There is no urban centre, only a few villages with less than 3200 inhabitants each; the mean population density was 19 inhabitants/km² in 2001 (Municipalité régionale de comté de Bellechasse 2010).

The Bellechasse region is subdivided into three landscape units. The first unit is a narrow (~10 km) plain bordering the St. Lawrence River. The altitude is low (15–50 m above sea level), and the plain is covered by sand and clay deposits. About 69% of the area is used for agriculture. The second unit is a narrow (~10 km) undulating plateau (mean altitude: 85 m above sea level) located between the plain and the Appalachian Mountains. More than half of the area of the plateau is covered with thick till. Forest covers approximately 63% of the area, while agriculture covers 34%. The third unit is mountainous (mean and maximum altitude: 115 and 900 m above sea level, respectively), and largely dominated (88% of the

area) by sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*) and balsam fir (*Abies balsamea*) forest. From the plain to the mountains, the mean annual temperature varies from 5.0 to 2.5°C, the mean annual precipitation from 900 to 1100 mm, and the mean annual snow precipitation from 300 to 350 cm. The length of the growing season ranges from 180 days on the plain to 160–170 days in the mountains (Robitaille and Saucier 1998).

In 2009, the total length of the road network in the study area was 1316 km (Energy, Mines and Resources Canada 1994, updated; Natural Resources Canada 1999, updated), excluding National Road 132 and Highway 20 (Fig. 1), which were not sampled for safety reasons (heavy traffic volume). Three types of roads (Fig. 2) are present: Regional Roads 216, 218, 277, 279 and 281 (all paved; total length: 137 km), paved local roads (total length: 1014 km), and



Fig. 2 The three different road types of the Bellechasse region (Quebec, Canada): **a** regional and paved, **b** local and paved, **c** local and unpaved (photographs: M. Joly)

unpaved local roads (total length: 165 km). In general, paved regional, paved local and unpaved local roads are 8.5-, 8.5- and 6.1-m wide, respectively (driving surface only), and are usually bordered by road verges 3.1-, 2.9- and 1.7-m wide (one side), respectively. In this study, a road verge is the distance separating the pavement, or the vegetation-free

driving surface of unpaved roads, from the beginning of the slope bordering the drainage ditch. Regional roads are used as links between population centres, and have a traffic flow of 380 (Regional Road 216) to 7100 (Regional Road 277) vehicles/day (Ministère des Transports du Québec 2007). Local roads are only used to access residences, farms or logging sites. Since regional roads are used much more frequently than local roads, they are disturbed more frequently, especially during winter for snow removal and for de-icing. In Quebec, the use of de-icing salt is dictated by the traffic volume, and may vary from 3 tons/km/year for roads with <500 vehicles/day to 69 tons/km/year for roads with >75000 vehicles/day (DiTommaso 2004; Lelong and others 2009). Most road verges in the Bellechasse region are mown at least once a year (from June to September), essentially for aesthetic purposes.

Data Sampling

Maps of the Bellechasse region (1:50000) produced by Energy, Mines and Resources Canada (1994) or by Natural Resources Canada (1999) were used for the selection of sampling sites. These maps were subdivided in 1×1 -km² squares (Universal Transverse Mercator grid), and each road type (paved regional, paved local and unpaved local) was clearly indicated. Each square ($N = 1026$) was classified according to the presence/absence of a particular road type, and 120 squares per road type were randomly selected for sampling. To keep the model simple, only squares with roads bordered on both sides by agricultural fields (cultivated or pastured) and/or old fields (with <50% tree or shrub cover) were selected. This information was available from the maps. A square was selected only once for a particular road type, but could be sampled several times if other road types were present.

The first 100 squares that were selected per road type were visited in September 2009, i.e., the time of year when common ragweed is particularly visible due to seed production. Several squares were immediately rejected during fieldwork because unpaved roads had recently been paved; they were replaced by one of the 20 additional squares that had been selected per road type. The mid-point of the road inside a selected square was chosen for sampling. Two 10-m long transects facing each other along both sides of the road were examined. The following data were recorded: (1) the location of the sampling site (with a geographic positioning system), (2) the presence of at least one individual common ragweed plant, (3) the agricultural use of the fields bordering the transects (cereal, soybean or forage cultivation, pasture, old field), and (4) the evidence of recent mowing of the road verges. If road verges had been recently mown, the presence of common ragweed in and under plant remains was very carefully checked.

The location of all sampling points was integrated in ArcGIS (ESRI 2006). Using the GIS and the data from the maps produced by Energy, Mines and Resources Canada (1994) or by Natural Resources Canada (1999), the forest cover (%) within a 750-m radius around each sampling site was measured as an additional explanatory variable. A 750-m radius was selected because forest cover data generated with this radius had a higher variance than with a 250, 500, 1000 or 2000-m radius (Fig. 3). We hypothesized that the higher the forest cover around a sampling site, the smaller the probability of finding common ragweed along the road verges. Since common ragweed is shade intolerant (Bassett and Crompton 1975), a low forest cover should provide more suitable sites for the establishment of common ragweed populations, which in turn could provide seed sources for nearby road verges. Finally, an additional explanatory variable, the Euclidean distance between a sampling site and the nearest waterway, was calculated using the GIS and the maps mentioned above to clarify the role of the hydrological network as a corridor facilitating the spread of common ragweed populations along roads.

Statistical Analyses

A binary logistic regression model (Hosmer and Lemeshow 2000) correcting for potential problems of variance heteroskedasticity (White 1980) was constructed with the data collected in the field or calculated with the GIS. The presence (or absence) of a common ragweed population in a sampling site was the dependent variable of the model. All the other variables were integrated into the model as independent (or explanatory) variables: sampling site (1) with a paved regional road, (2) with a paved local road, (3) with road verges recently mown, (4) bordered by cultivated fields—cereals, (5) bordered by cultivated

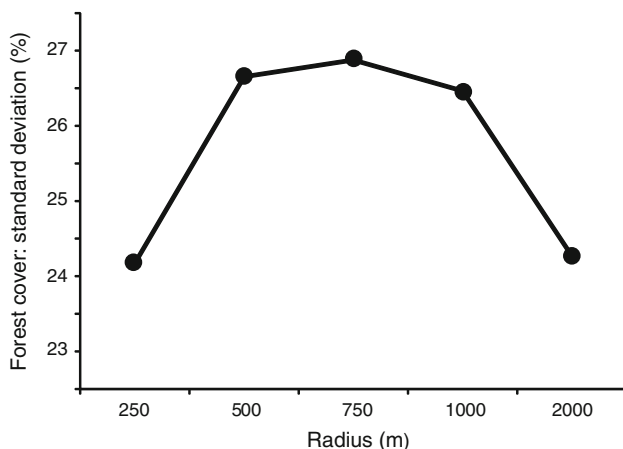


Fig. 3 Standard deviation of the forest cover data calculated with different radii around the sampling points that have been used to study the spatial distribution of common ragweed (*Ambrosia artemisiifolia*) along road types of the Bellechasse region (Quebec, Canada)

fields—soybean, (6) bordered by cultivated fields—forage, (7) bordered by pastures, (8) bordered by old fields, and with the (9) forest cover (%) and (10) distance (m) to the nearest waterway. To avoid multicollinearity, the unpaved local road variable was used as reference for road types in the logistic regression model. For each type of road, agricultural use or mowing, a value of 1 was attributed in the model for positive cases (presence of the characteristic), or 0 for negative cases (absence of the characteristic). The Stata and Matlab software applications (LeSage 1999; Gilat 2008; StataCorp LP 2009) were used for calculations or to test for possible influence of spatial autocorrelation on the model (Moran 1950). Three approaches were used to evaluate the goodness-of-fit of the model. The first relied on the pseudo R^2 measure (McFadden 1974), the second on the comparison of predicted probabilities with sample frequencies (Hosmer and Lemeshow 2000), and the third on the comparison of predicted outcomes with actual outcomes using a classification table (Cameron and Triverdi 2009).

Results

Of the 300 sites sampled in September 2009 (located in 242 of the 1026 squares of 1 km²), six sites were subsequently rejected because it was not possible to clearly identify the agricultural use in the fields bordering the roads. Common ragweed populations were found in all parts of the study area, although they were more abundant in the plain bordering the St. Lawrence River and in the plateau than in the mountainous section (Fig. 1). Common ragweed was found at almost all sampling sites located along paved regional (97%) and paved local (81%) roads. However, verges of unpaved local roads were rarely (13%) colonized by the plant.

The statistical model explained 53% of the total variance (presence/absence). The Hosmer–Lemeshow statistic, which was not significant at more than 85%, indicated that there was no significant difference between field observations and model predictions for presence/absence. Moreover, the model correctly predicted 89% of the presence or absence of common ragweed along the roads of the Bellechasse region (Table 1), with a better prediction of presence (93%) than of absence (83%). Four (paved regional road, paved local road, recently mown verges and forest cover) of the nine independent variables that were used in the logistic regression model were significant ($P < 0.05$; Table 2). Regional and local paved roads were weighted more heavily in the model (Wald's statistic), but the probability of finding a common ragweed population along a road (odds ratio) was higher along paved regional roads (387× greater than unpaved local roads) than along paved

Table 1 Results of the binary logistic regression model that was used to establish a link between the presence (or absence) of common ragweed (*Ambrosia artemisiifolia*) populations along the roads of the Bellechasse region (Quebec, Canada) and some environmental variables: classification table comparing fitted probabilities and dichotomous outcomes, for a cut-off criteria probability of 0.5

Prediction (model)	Observation (in the field)		
	Presence	Absence	Total
Presence	176	18	194
Absence	13	87	100
Total	189	105	294

Table 2 Results of the binary logistic regression model that was used to establish a link between the presence of common ragweed (*Ambrosia artemisiifolia*) populations along the roads of the Bellechasse region (Quebec, Canada) and some environmental variables: details associated with each variable

Variable	Variable type	β	Odds ratio	Wald	P
Paved regional road	Binary (0/1)	5.96	387.10	65.05	<0.001*
Paved local road	Binary (0/1)	3.86	47.62	53.73	<0.001*
Recently mown road verges	Binary (0/1)	-0.59	0.55	4.81	0.028*
Forest cover (% 750-m radius)	Continuous	-1.68	0.19	4.35	0.037*
Bordered by old fields	Binary (0/1)	1.16	3.18	3.16	0.075
Bordered by pastures	Binary (0/1)	0.60	1.83	1.09	0.297
Bordered by cultivated fields (cereals)	Binary (0/1)	0.28	1.32	0.27	0.605
Bordered by cultivated fields (forage)	Binary (0/1)	0.09	1.09	0.04	0.851
Bordered by cultivated fields (soybean)	Binary (0/1)	0.09	1.10	0.02	0.893
Distance to the nearest waterway (m)	Continuous	0.00	0.19	0.02	0.902
Constant		-1.72		5.14	0.023

The unpaved local road variable was used as reference for road types in the logistic regression model

* Significant at $P < 0.05$

local roads (48× greater than unpaved local roads). The model also indicated that in 2009, there were significantly lower chances ($\times 0.55$) of finding a common ragweed population on a recently mown road verge than on an unmown road verge, and that the chance of finding a common ragweed population along a road declined with an

increase of the forest cover within a 750-m radius. It should be noted that finding common ragweed remains was an easy task on mown road verges, and that more paved regional roads were mown (57% of sampling sites) than paved local (38%) or unpaved local (12%) roads.

There was no spatial autocorrelation problem among residuals, as indicated by the Moran's I statistic. Calculations of the statistic using five (-0.010) or ten (0.021) neighbours are not statistically different from the theoretical mean value (-0.003). Thus, the presence of spatial autocorrelation among residuals is rejected at a significance level of $P < 0.05$ (five or ten neighbours).

Discussion

It is possible to correctly predict (success rate: 89%) the spatial distribution of the common ragweed along the roads of an agricultural landscape using a logistic regression model and without generating spatial dependence among residuals. The model requires few variables that are easily collected in the field or with a GIS. It explains more than 52% of the variance. In southern Quebec, paving a road is literally paving the way for an opportunistic species like the common ragweed. The plant is abundant on the verges of paved roads, and rare along the verges of unpaved roads. A high forest cover within a 750-m radius significantly reduces the probability of the presence of a common ragweed population along a road (probably because individuals are less numerous in forested areas), even when the sampling site is bordered on both sides of the road by agricultural fields, but the weight of this explanatory variable is not very high compared to road types.

The model built with common ragweed distribution data supports the idea that the attributes associated with paved roads highly influence the spread of an opportunistic invasive species. Specifically, larger verges provide more habitat, higher traffic volume favours seed dispersal, and more road maintenance disturbs soil, creating propitious conditions for species like common ragweed (Gelbard and Belnap 2003; Truscott and others 2005; Meunier 2008; Lelong and others 2009). In southern Quebec, paved roads, and especially the heavily used national or regional roads, require a high level of maintenance due to a harsh winter climate. Paving and road-sides are frequently repaired due to freeze-thaw cycles: southern Quebec roads are subjected to freezing temperatures 147–218 days/year, and the frozen soil layer may reach a thickness of 1.2–3.0 m, causing the pavement to crack (Ministère des Transports du Québec 2010). Winter snow removal (heavy shovels pushed by trucks) also disturbs the soil of the road verges. Soil disturbance from these maintenance activities facilitates the establishment

of common ragweed; the seeds of this plant only germinate if they are located within 5 cm of the soil surface (Bassett and Crompton 1975; Willemsen 1975). Experimental studies have shown that disturbing the soil surface not only stimulates the germination of common ragweed seeds (Rothrock and others 1993; Fumanal and others 2008a, b), but also increase the number of leaves, the stem biomass and the seed production of emerging individuals (MacDonald and Kotanen 2010). Large quantities of de-icing salts are also spread in winter on national and regional roads to prevent car accidents. Common ragweed populations growing on Quebec's road verges receive frequent applications of salt during the winter months, and have developed a greater ability to germinate under saline conditions than populations located along local roads or in agricultural fields (DiTommaso 2004). All these factors (wider road verges, disturbance, pollution) contribute to a greater abundance of common ragweed along major highways than along local roads.

Our model suggests that road verges that have been recently mown (at the end of August or in September) are significantly less populated by common ragweed than road verges with no evidence of recent mowing. This result should nevertheless be interpreted with caution. The efficacy of mowing to prevent the expansion of common ragweed populations is not proven, and may depend on timing (Vincent and Ahmim 1985; Bohren 2008; Vitalos and Karrer 2009). Regardless of timing, a single mowing effort is apparently insufficient to substantially reduce the number of flowering stems (Delabays and others 2008). In the Bellechasse region, our model suggests that mowing may be effective, but without details on the historical patterns of mowing activities for each site, it is difficult to determine which common ragweed management procedure was truly effective.

Results of this study can be used to analyse management prioritizations that have been developed over the years to control this highly problematic weed. Emphasis has been placed on the herbicidal control of common ragweed in agricultural fields, which is understandable considering that yield losses in corn and soybean fields may reach 65–70% at high common ragweed density (Weaver 2001; Cowbrough and others 2003; Saint-Louis and others 2005; Clay and others 2006). However, controlling common ragweed in fields without taking roadside populations into account is questionable, since, as this study and others (Lavoie and others 2007; Simard and Benoit 2010) suggest, the common ragweed first invades the roads of a region, and then the agricultural fields.

The Department of Transportation of Quebec has a protocol requiring the mowing of roadsides (national and regional roads) at least twice per year (and especially at the end of August) for the control of common ragweed

(Ministère des Transports du Québec 1994, 2008). However, we noted in September 2009 that a large proportion (43%) of regional road verges were not recently mown, which suggests that the protocol is not consistently followed. Moreover, few municipal managers in charge of mowing the roadsides of local roads are aware of common ragweed or of protocols for its control. Most local roads are mown once or twice per year, essentially for aesthetic reasons, usually at the beginning of the summer; there is no systematic mowing pattern (personal communications with managers). This is problematic, since verges of paved local roads are also highly invaded by the plant. The paved local road network is also much more extended (7×) than the regional network. Considering the huge pollen production of each common ragweed individual, populations along both regional and local paved roads must be included in a regional control strategy.

The influence of road type on the distribution of a plant invader observed for the common ragweed is certainly not unique. Considering the omnipresence of roads, more attention should be paid to the impact of road type on the spread of invaders, because road networks are still rapidly expanding and improving throughout the world, especially in developing countries (Hawbaker and others 2006; Sharma and Raghubanshi 2009; Li and others 2010). This case study also shows that control strategies may be unsuited to the spatial distribution of invasive species, and that the absence of concerted action could lead to ineffective management of problematic plants. For the specific common ragweed case, our study suggests that attention on surveying and treating incipient populations should be focused on gravel roads (to eliminate potential invasion foci), while more extensive and intensive control efforts are needed along all paved roads, and not only along high-traffic ones.

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