Forest susceptibility and vulnerability to Hemlock Looper as a framework for developing an optimal detection and monitoring strategy

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Abstract

This progress report presents the first analyses of a study started in July 2012 in the Laurentian Wildlife Reserve, Quebec, where defoliation was noticed in balsam fir stands of the Montmorency Forest, which is owned by Laval University and serves for teaching purposes and experimental research. The Hemlock Looper (HL) and the Rusty Tussock Moth (RTM) were then both observed in the area. Our data show that the HL was responsible for observed defoliation. Also, there was no correlation in the abundance of these two species in sampled stands. The RTM population collapsed due to a disease but HL defoliation continued in 2013. Pure balsam fir stands were more defoliated than any other stand type. Over mature stands were generally more susceptible but mature and young stands were also affected by the HL. Irregular stands were the least affected ones. Egg estimates on foam traps were significantly correlated with those obtained from branches. We used successfully fall 2012 egg estimates from foam traps to predict 2013 defoliation at the stand level. These predictions could be improved by adding other variables, the best predictions involving latitude and estimates of pupal populations and interactions between variables. Estimates of egg mortality indicate very low levels of parasitism by *Telenomus* spp with some southern stands showing higher levels, suggesting climatic constraints for this parasitoid. Winter HL egg mortality was generally high but variable. Historic data from Montmorency Forest show that the frequency of harsh winters decreased over the last 50 years, suggesting that climate warming could be linked with the ongoing HL outbreak in the Laurentian Wildlife Reserve.

Résumé

Ce rapport d'avancement présente les premières analyses d'une étude débutée en Juillet 2012 dans la Réserve Faunique des Laurentides, Québec, où des défoliations ont été observées dans la sapinière de la Forêt Montmorency, propriété de l'Université Laval et qui sert à l'enseignement et à la recherche forestière. L'arpenteuse de la pruche (AP) et la chenille à houppes rousses (CHR) étaient alors toutes deux observées dans la région. Nos données montrent que l'AP était responsable des défoliations observées et qu'il n'y avait pas de corrélation entre l'abondance des deux espèces dans les peuplements échantillonnés. Les populations de la CHR se sont écroulées à l'automne 2012 cause d'une maladie mais les défoliations de l'AP se sont poursuivies en 2013. Les sapinières pures étaient plus défoliées que tout autre type de forêt. Les peuplements sur-matures étaient généralement plus susceptibles bien que les peuplements matures et jeunes étaient aussi affectés par l'AP. Les peuplements irréguliers étaient les moins affectés. Les estimés de

populations d'œufs à partir de bandes de foam étaient significativement corrélés avec ceux obtenus à partir des branches. Les estimés d'oeufs obtenus à partir de bandes de foam à l'automne 2012 permettent de prédire la défoliation de 2013. Ces prédictions peuvent être améliorées en ajoutant d'autres variables, les meilleures prédictions utilisant aussi la latitude et des estimés de populations de chrysalides ainsi que les interactions entre les variables. Les estimés de mortalité des œufs indiquent de très bas taux de parasitisme par *Telenomus* spp, les sites les plus au sud montrant les plus haut taux de parasitisme ce qui suggère des contraintes climatiques pour l'espèce. Par ailleurs, la mortalité hivernale des oeufs était généralement haute, bien que variable. Les données historiques de la Forêt Montmorency montrent que la fréquence des hivers froids a diminué depuis 50 ans, suggérant que le réchauffement climatique puisse être lié à l'épidémie actuelle d'AP dans la RFL.

Introduction

In Eastern Canada, most Hemlock Looper outbreaks have been reported near large bodies of water, such as in Newfoundland, Anticosti Island, the tip of the Gaspe peninsula or the North Shore of the St Lawrence river in Quebec (Hébert and Jobin 2001), suggesting that this pest might be associated with a maritime climate (Jobin 1973, 1980). However, during summer 2012, an incipient HL outbreak was reported for the first time in the Laurentian Wildlife Reserve (LWR), which is located 70 km north of Quebec City, far away from usual outbreak areas. The LWR is a hilly area with an average altitude of 750 m and it is known to be much colder than the maritime areas usually affected by the HL. For instance, the average annual temperature in the LWR is 0.3°C compared with 5.1°C in Corner Brook, NL. This warns us that, in the context of climate change, HL outbreak could occur in areas where it has never been observed before. Therefore, we need to determine in which type of forest and conditions HL could become an issue. In the past, HL outbreaks usually occurred in stands in which mature and over mature balsam fir predominated (Carroll 1956). However, this observation was done in areas where mature, over mature and even old-growth balsam fir stands were still abundant. The forest of the LWR is much more diversified in terms of age structure as it has been largely harvested during the 20th century. As we are at the very beginning of the outbreak, it is possible to determine in which types of forest began this outbreak and this should help to define forest susceptibility to this pest. Moreover, understanding how the outbreak will develop in this new context is important for improving our ability to survey HL populations, forecast defoliation and thus better support pest management decisions. Decisions for spraying Bt are based on fall HL egg density. However, relationships between fall egg densities and resulting defoliation the following summer need to be improved particularly for predicting moderate and moderate-high defoliation. Linking overwintering populations and defoliation the following year is a difficult task because important mortality can occur at the egg stage during winter (due to low temperatures; Rochefort et al. 2011; Delisle et al. 2013) and/or through important parasitism by *Telenomus coloradensis*, which can reach very high levels in spring (Hébert and Brodeur 2013; Hébert et al. 2001, 2006; Carleton et al. 2009, 2010; Legault et al. 2012, 2013). These links remain to be done because it has always been difficult to run such studies due to the short duration of HL outbreaks and also because of the poor accessibility of stands.

The LWR outbreak

The Rusty tussock moth, *Orgyia antiqua* L. (Lepidoptera: Lymantriidae; hereinafter RTM), an exotic species now established in most Canadian provinces was also present and relatively abundant in the LWR when the outbreak was detected in early July 2012. Its role in observed defoliation was then uncertain. A working group was formed two weeks later with people representing various organisations and interests: CFS and iFor consortium involved in research, MRNQ and SOPFIM involved in pest and strategic land management, Montmorency Forest and the Seigneurie de Beaupré (large private land owner) which are involved in operational land management, and Parc de la Jacques-Cartier which is a protected area with a conservation mandate. The mandate of the working group is to *"Develop knowledge, tools and decision support systems for improving integrated management of Hemlock Looper and other associated insects, in order to reduce potential impacts of forest pests"*. Combined efforts of this group allowed implementing rapidly a widespread plot network aimed to provide data for answering research questions for assisting managers in the process of taking decisions.

Objectives of the study are:
1) Determine the respective roles of the HL vs RTM in 2012 defoliation
2) Characterize the most susceptible stands to the HL. It will help answering two burning questions that came rapidly from partners:
   a. Are over mature stands linked with this outbreak?
   b. Does forest management favoured HL?
3) Improve HL defoliation forecasting on the basis of egg populations
4) Determine how climatic conditions influence egg mortality and how they shape the ongoing outbreak
5) Determine how the surrounding matrix influence HL populations and defoliation
6) Develop an optimal sampling strategy, taking into account stand and landscape characteristics as well as spatial autocorrelation, to sample HL populations

This progress report will address the first four objectives through preliminary analyses but data will allow much deeper analysis. This will eventually lead to integrating objectives 5 and 6.

Materials and methods

Data were collected through a widespread network of plots scattered over a territory covering over 1000 km^2. The first step in the establishment of this network goes back to late July 2012, three weeks after outbreak discovery. We sampled pupae in 125 stands, mostly at Montmorency Forest which has a well-developed road network and permanent sample plots (Figure 1-A). With the help of various partners, this network was expanded to 280 stands for sampling eggs (Figure 1-B). Among these 280 stands, we estimated egg mortality in 170 stands. This network was reduced in 2013 due to budget constraints. We were able to sample 146 stands for pupae, 150 for eggs and 50 for egg mortality.

Pupal sampling

Pupation shelters were used to estimate HL populations and to assess pupal mortality (Hébert et al. 2004). These shelters are made with a drainage cylinder (10 cm in diameter x 27.5 cm in length), on which three 5-cm-diameter circular holes are drilled along vertical rows on opposite sides of the cylinder (Figure 2-A). A 20 x 90 cm burlap strip is rumpled inside the shelter. This

shelter was also efficient for sampling the rusty tussock moth (RTM). Dahlsten et al. (1992) sampled another tussock moth, *Orgyia pseudotsugata*, with an artificial pupation shelter.

One shelter was placed at breast height (DBH) on the south side of each of 5 co-dominant trees. Shelters were set up by late July and recovered three weeks later when all larvae had pupated. All HL pupae and RTM cocoons were counted, as well as braconid cocoons and HL dead larvae and prepupae. Braconid cocoons were kept in Solo cups until adult emergence to obtain specimens that could be identified. Non-emerged pupae were reared until moth or parasitoid emergence. Pupae that died without parasitoid emergence were dissected to determine the causes of mortality whenever possible. Pupal mortality caused by parasitoids was determined by observing the different types of slits and holes left on the pupa after emergence (Hébert et al. 2004). When mortality cause could not be determined, we assigned these individuals to an unknown category.

Moth sampling
Moth data were collected in 12 plots of the network at Montmorency Forest in which the iFor consortium was already running an experiment aimed to measure the impact of partial cutting on pest dynamics. Two Luminoc® traps (Jobin and Coulombe 1988; Figure 2-B) were set up in each stand and each trap was equipped with a 1.8W blue light tube and a Vapor Tape II strip for killing moths. Traps were placed at least 100 m apart from each other and operated until the end of HL moth flight activity. These stands were already sampled in 2010 and 2011 and we continued monitoring them in 2012 and 2013. Thus, our data on moth abundance cover the last 4 years.

Egg sampling
Foam traps can be used successfully for surveying HL oviposition (Hébert et al. 2003) and provide assessment of local overwintering populations. Foam strips (17 x 30 cm) were stapled at DBH on the south side of each of 5 co-dominant trees in each stand (Figure 3-A). Previous observations have shown that moths aggregate under these strips (Figure 3-B). Then, to make it easier for moths to access the underside of foam strips, we just bend foam strips while stapling them on tree boles (Figure 3-A). Eggs are firmly attached to the artificial fibers of the foam (Figure 3-C) which makes this technique quite robust. Also, MRNQ collected 1-m branches in the mid part of the lower crown (Dobesberger et al. 1989) of each of 3 trees per stand. Eggs were extracted in the lab following the technique of Otvos and Bryant (1972). These branches were collected in a subset of our network (n=97 stands) to verify the relationship between egg population estimate obtained with foam strips vs 1-m branches.

Egg mortality
Females were collected on the field and allowed to oviposit on 4-cm foam disks in laboratory. These sentinel traps were placed at DBH on the south side of the bole of trees in late October. Five foams were simply stapled on tree boles to estimate parasitism (Figure 4-A) while five foams were placed in the middle of a ventilated plastic bottle (Figure 4-B) that did not allow access to parasitoids. Traps were collected between June 6 and 14. Eggs were removed from foams and reared to estimate winter mortality and parasitism.

Stand description
We used ecoforest maps to determine stand characteristics. We concentrated on two variables: stand type and stand age. We also used defoliation maps produced by MRNQ to estimate

defoliation of each sampled stand. According to Iqbal and McLean (2010), we calculated a cumulative index of defoliation, from 1 to 6 (1=1 year of light defoliation; 2: 2 years of light defoliation or 1 year of moderate defoliation… 6=2 years of severe defoliation). In 2013, we also estimated overall defoliation of 10 co-dominant trees in 50 stands.

Data analysis
In order to determine the respective roles of the HL and the RTM in 2012 defoliation, we used Anova to compare pupal population estimates as a function of MRNQ defoliation classes. We also used regression to determine if there was a correlation between pupal population estimates of the two species.

Stand susceptibility is defined as the probability that a forest could be defoliated by an insect (MacLean 1980). As a first step, we compared the distribution of defoliated stands vs stand types and ages with that of stands available across a 1600 km^2 area that encompassed defoliated areas. Then, we used chi square analysis to determine if defoliation vs stand types or ages followed the same distribution of stands available across the landscape.

We used regression to verify if population estimates obtained with foam traps were correlated with those from 1-m branches. We also used regression to verify how egg estimates on foam traps in fall 2012 allowed predicting defoliation in 2013. Other variables were then added to test whether they could improve prediction.

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Results

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Respective roles of Hemlock Looper and Rusty tussock moth in 2012 defoliation
The number of HL pupae or RTM cocoons per pupation shelter represent the best estimates of larval populations of each species in a stand and should be linked with the resulting defoliation. Increasing populations of HL pupae were found from lightly to highly defoliated stands while RTM cocoons did not differed between the three defoliation classes (Figure 5). Moreover, HL pupal estimates and RTM cocoons estimates were not correlated at the stand level (Figure 6). RTM cocoons were strongly affected by a disease and only 3% survived in 2012 while HL pupal survival accounted for 52%. No RTM cocoon was collected in 2013 but HL was still present.

Stand susceptibility to HL – preliminary analysis using defoliation
The LWR landscape studied is dominated by balsam fir forest with pure stands covering 33% of the land area, while fir stands with white birch and black spruce as companion species represent respectively 30% and nearly 14%, for a total of 77% of the land area. All types of stands in which defoliation was observed contained balsam fir but overall, 90% of defoliated stands were dominated by balsam fir with pure stands being the most defoliated, encompassing 52% of defoliated stands compared with 25% and 12% for fir stands with white birch and black spruce as companion species (Figure 7). This distribution of defoliated stands differed significantly from that of available stands (X^2=20.02, df=4, P=0.00049).

As pure balsam fir stands are the most susceptible to HL defoliation, we focused our attention on these stands for determining if old stands were more susceptible to the HL. Among pure balsam fir stands, most defoliated areas belong to the 50-yrs age class (19.6% of overall defoliated area), followed by the 30-yrs (15%) and 70-yrs (14.6%) age classes (Figure 8-A). However, the 70-yrs

age class represented only 5.8% of the available stands compared to 10.6% and 8.9% for the 50-yrs and 30-yrs ages classes respectively. These distributions differ significantly (X^2=27.167, df=6, P=0.0001). We used a ratio of defoliated / available stands to illustrate it (Figure 8-B). A ratio higher than 1 indicate an age class more susceptible to the HL, the reverse being true for a ratio lower than 1. The 70-yrs age class had the highest ratio but the 50 and 30-yrs age classes also showed high ratios (even the 10-yrs age class was >1). The ratio is meaningless for the 90-yrs old age class as it represented only 0.24% of the territory but it should be noticed that both young and old irregular fir stands were much less defoliated than any regular aged stands.

Most of these 70-yrs defoliated stands were located in the Parc de la Jacques-Cartier at least 10 km north of the most important patches of 2012 defoliation which occurred in 50-yrs old stands at the Montmorency Forest, and in 30-yrs old stands at Camp Mercier, located south of the the Montmorency Forest (Figures 9 and 10). Young and old irregular pure balsam fir stands were mostly scattered in the Parc de la Jacques-Cartier and at the north of the Montmorency Forest. In fact, most young and old irregular fir stands (when considering all stand types) were in these areas (Figure 11).

Defoliation forecasting
Egg population estimates from foam traps were significantly correlated with those obtained from 1-m branches (Figure 12). Using estimates from foam traps, a significant relationship was obtained between egg populations in fall 2012 and resulting defoliation in 2013 (Table 1). This relationship explained 47.4% of the variability in the model (Figure 13). Adding winter egg mortality into the model increased the strength of the relationship to 54.3% and adding the interaction between winter mortality and latitude allowed explaining 63.1% of variability (Table 1). Using latitude as a surrogate for egg mortality into the model, which is cheaper and faster to obtain for management purposes, allowed explaining 52.6% of the variability in the relationship. A model using only egg population estimates in fall 2012 and surviving pupae estimates (and their interaction) provided better prediction of 2013 defoliation (r^2=.748). The best model for predicting 2013 defoliation was obtained by considering egg population estimates, pupal population estimates, latitude and interactions between eggs and both variables (r^2=.817).

Egg mortality
Winter mortality was generally high and *Telenomus* parasitism low in the studied area. Similar results were obtained in a previous study in the Lower St-Lawrence when winter mortality was high (Figure 14). However, when winter mortality was lower, parasitism was much higher. We measured the lowest winter mortality and the highest rates of parasitism in the southern part of the studied area (Figure 15), which is consistent with this previous study.

Discussion

Our results indicate that the HL was responsible for most of the defoliation observed in LWR. The absence of correlation between the HL and the RTM suggests that their simultaneous presence might have resulted from random events or from similar responses to abiotic variables.

Our results showed that pure balsam fir stands are much more susceptible to the HL than any other type of stands and that stand age appear less important than stand type, even if the 70-yrs age class was slightly more susceptible. Moreover, young and old irregular stands were much less

susceptible than even-aged stands. These stands are mostly located in the Parc de la Jacques-Cartier, where the landscape has been shaped by the last Spruce budworm outbreak, and at the north of the Montmorency Forest, where management aimed to maintain woodland Caribou led to maintain greater cover of over mature stands. This suggests that forest management which generates even-aged stands are more susceptible to the HL than irregular stands.

It has always been difficult to address the issue of predicting HL defoliation because of the ephemeral nature of outbreaks, their control through Bt spraying and also because of the inaccessibility of the territory in previous outbreaks. In the LWR, all conditions to run such study were met: there has been no spray program, the outbreak did not collapsed and we have been able to estimate egg population in numerous stands in fall 2012. Defoliation can be predicted with 47% accuracy on the basis of egg population estimates from foam traps. This accuracy can be improved up to 81% by adding pupal population estimates. Interactions between egg and pupal estimates are particularly insightful in this regard.

Very low *Telenomus* parasitism (< 2%) was measured in the Montmorency Forest in 2010 and 2011 (unpublished data from Legault), which is in accordance with results presented here. In fact, *Telenomus* reaches its highest levels in southern stands, where climatic conditions are probably less restrictive for this species, which has a supercooling point estimated at -30.6°C (Legault et al. 2012). On the other hand, the frequency of harsh winters is decreasing in LWR, providing favorable conditions for HL population buildups, particularly if temperatures are still too low for allowing efficient parasitism by *Telenomus*. A recent study showed that an exposure of 2 hours at -37°C is lethal to HL eggs (Delisle et al. 2013). This temperature has been reached 6, 7, 4, 4 and 2 times over the last 5 decades. The lowest winter temperature was recorded in 2009 in the LWR (Figure 13). Nevertheless, populations bounced back and increased rapidly to reach outbreak level in 2012. In 2010, moth populations were already twice higher than in endemic populations, as measured in a previous study in the Lower St Lawrence region in Quebec (Figure 14). Thus, moth survey could also be useful in an early warning system for assessing HL outbreak risk. This new outbreak in an unexpected area calls for increasing surveillance of HL populations, particularly because regional ecotypes react differently to ecological conditions (Berthiaume et al. 2009; Rochefort et al. 2011).

Acknowledgments

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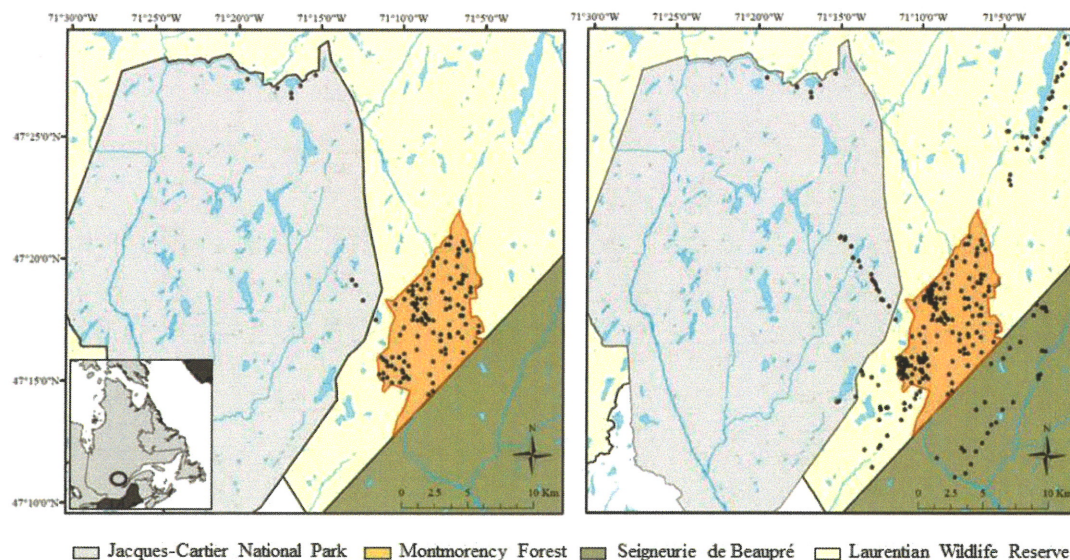
Figure 1: (A) Map showing the 125 study sites established in July 2012 to sample Hemlock Looper pupae and Rusty Tussock Moth cocoons in Forêt Montmorency and Parc de la Jacques-Cartier and (B) the more extensive network (n=280 sites) implemented in Fall 2012 to sample HL eggs in surrounding parts of the Laurentian Wildlife Reserve.

Figure 2: (A) Pupation shelter attached on tree bole for sampling HL pupae and RTM cocoons and (B) Luminoc® trap attached to a branch for sampling HL moth.
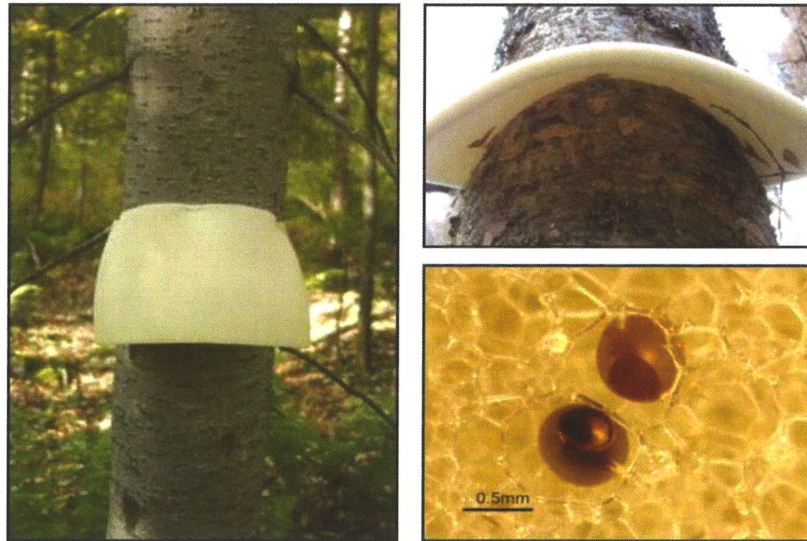
Figure 3: (A) Foam strip stapled on tree bole, (B) moths resting under a strip and (C) eggs deposited into the foam.

Figure 4: (A) Sentinel trap (foam disk with HL eggs) for estimating egg parasitism (mostly by *Telenomus,* shown in the left corner) and (B) sentinel trap placed inside a ventilated plastic bottle which protects eggs from parasitism for estimating winter mortality.
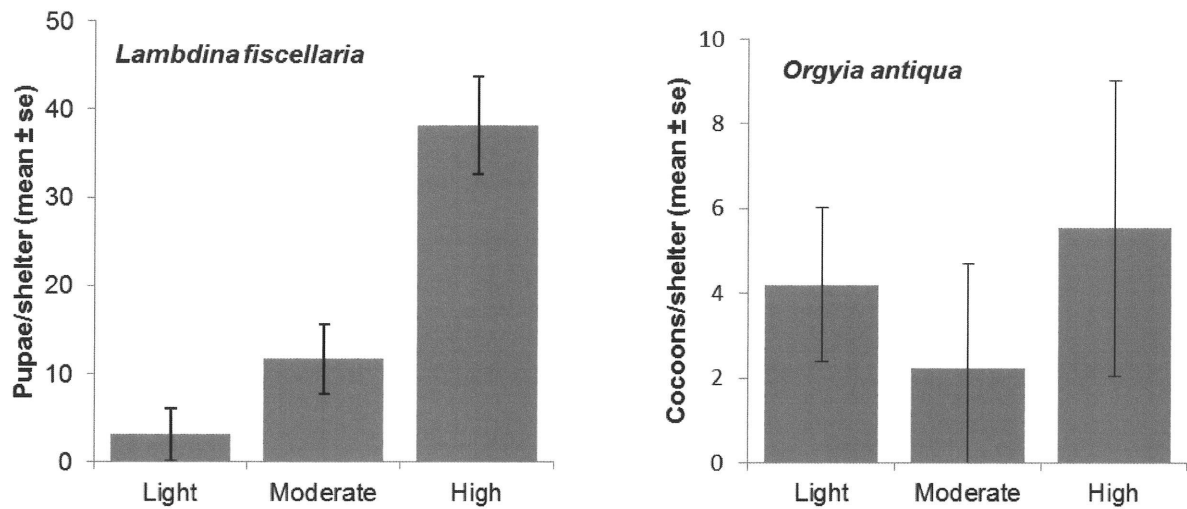
Figure 5: Hemlock Looper and Rusty tussock moth pupal population estimates as a function of stand defoliation in 2012. The High defoliation class was significantly different from the light and moderate classes for *Lambdina fiscellaria*.
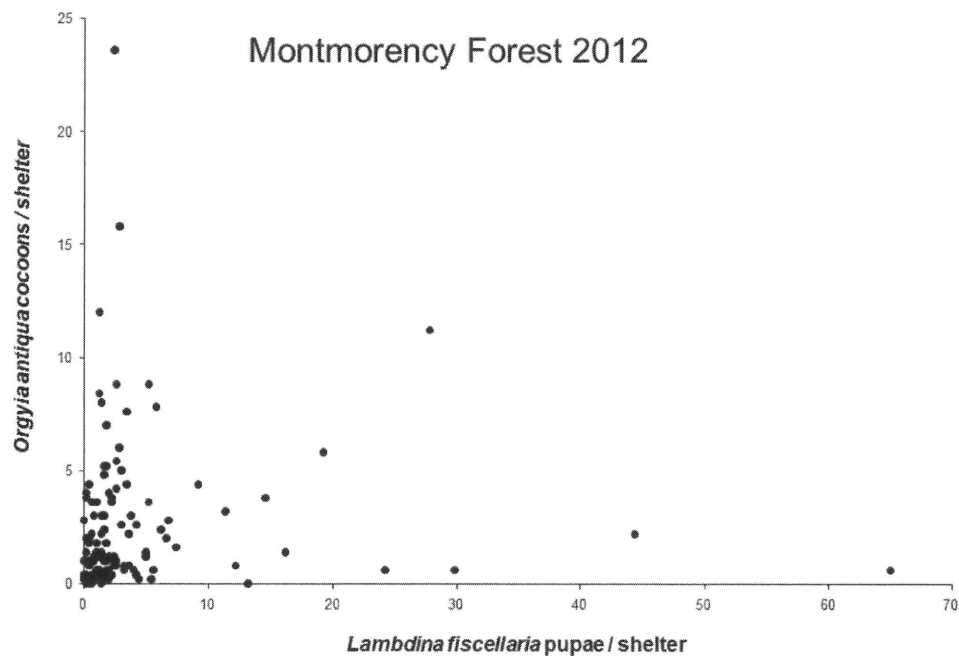
Figure 6: Relationship between Hemlock Looper and Rusty tussock moth population estimates in Laurentian Wildlife Reserve in 2012.
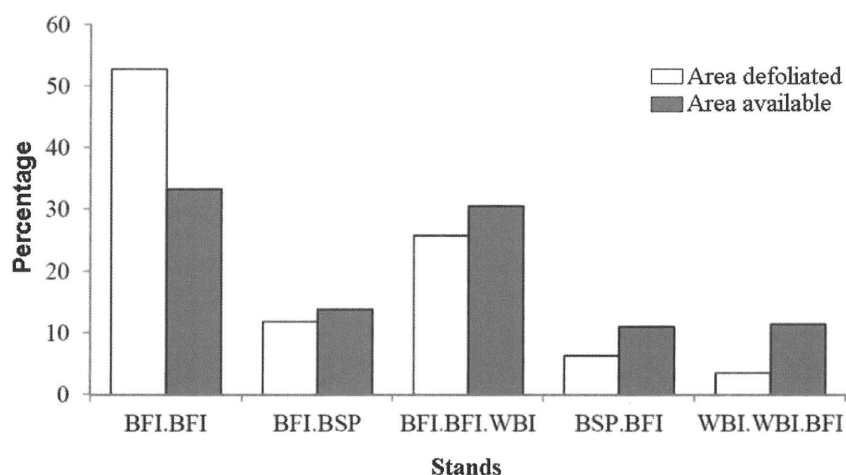
Figure 7: Comparison in areas of defoliated vs available stands as a function of stand type in a 1600 km^2 area in the LWR.
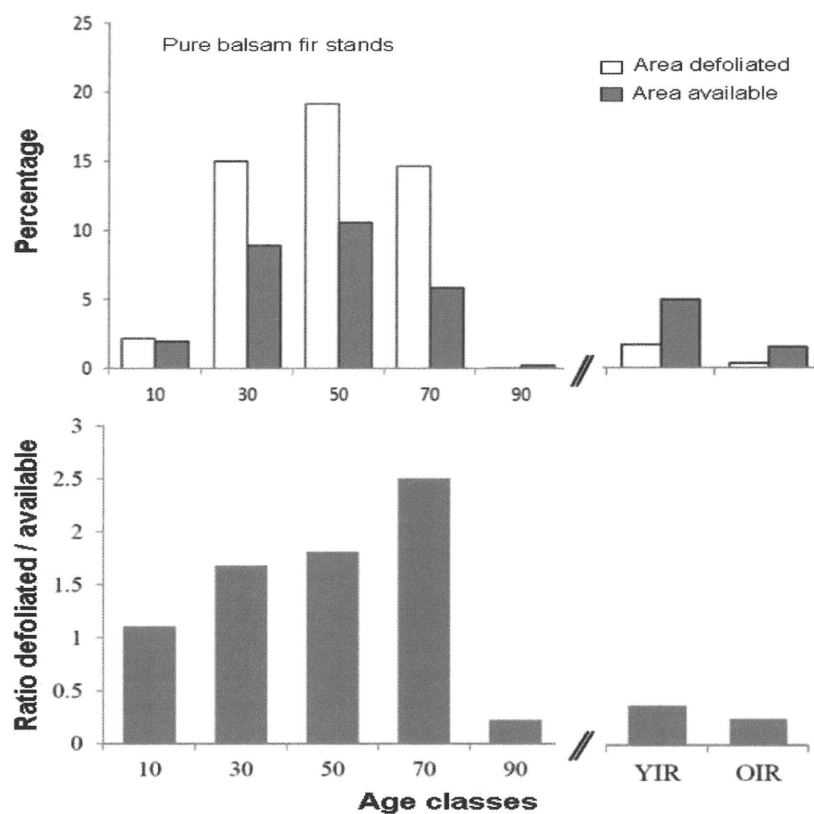
Figure 8: (A) Comparison in areas of defoliated vs available pure balsam fir stands as a function of stand age in a 1600 km^2 area in the LWR and (B) ratio showing trends in susceptibility in each age class. A ratio higher than 1 indicate a group more susceptible to the HL while the reverse is true for ratio lower than 1.
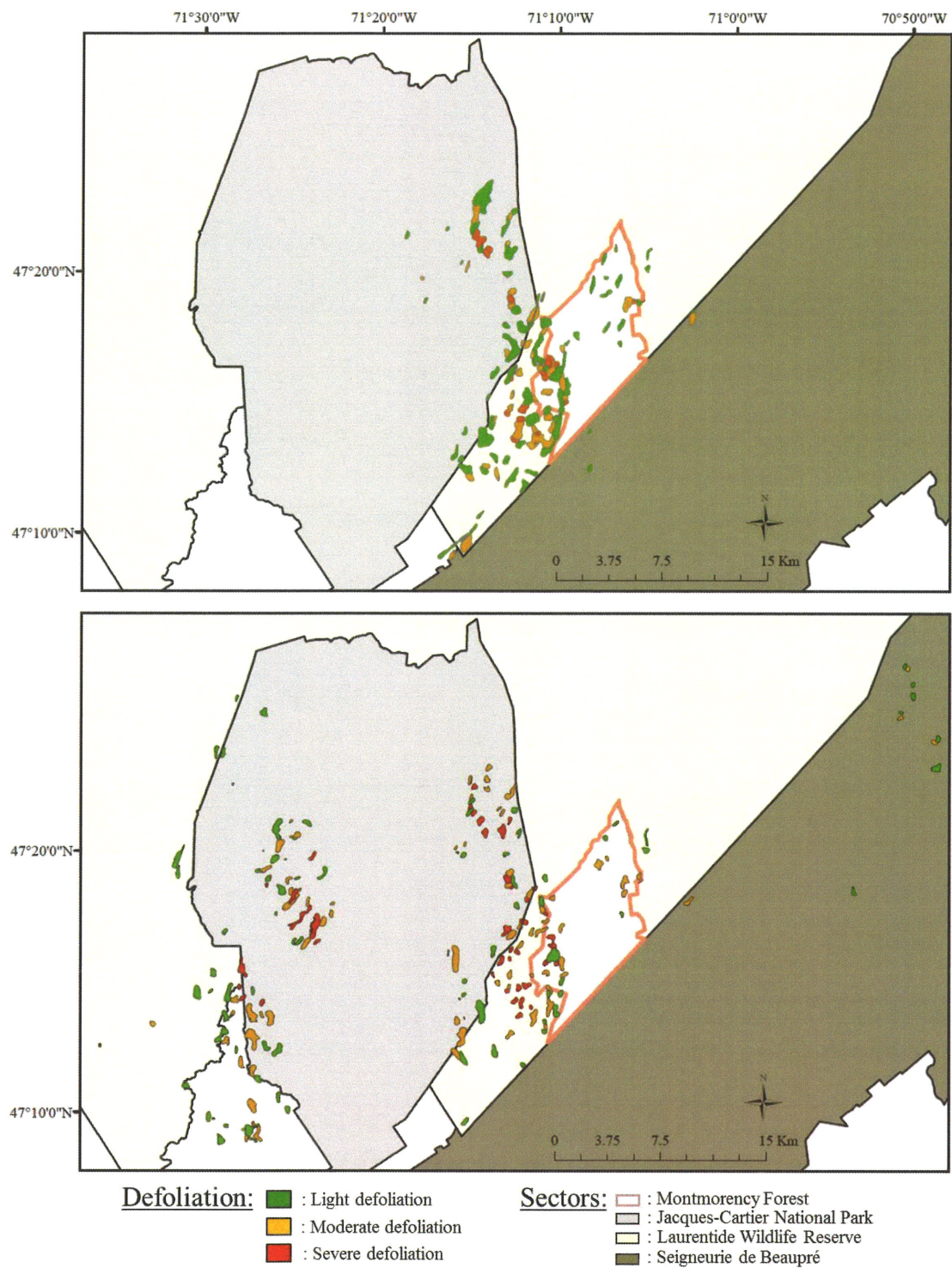
Figure 9 : Defoliated areas by the HL in 2012 (upper map) and 2013 (lower map) in the LWR.
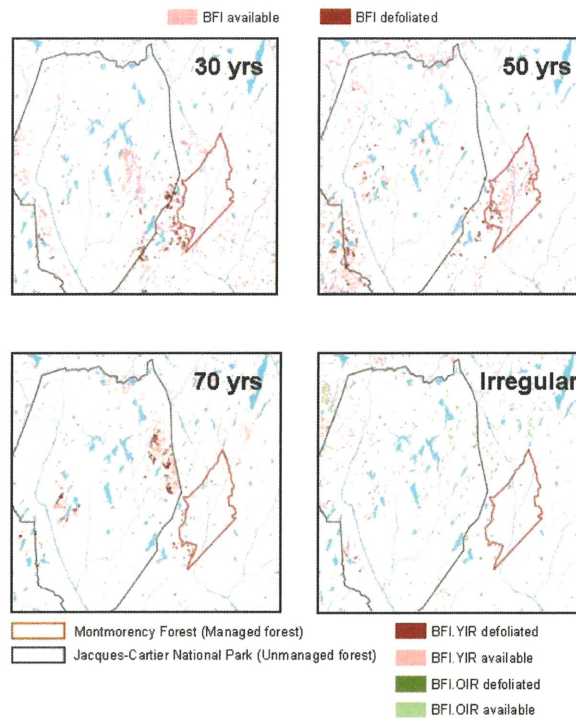
Figure 10: Maps showing the spatial distribution of the 30, 50 and 70-yrs old regular pure balsam fir stands and of young and old irregular pure balsam fir stands, and their respective defoliation, across the landscape in a 1600 km^2 in the LWR.
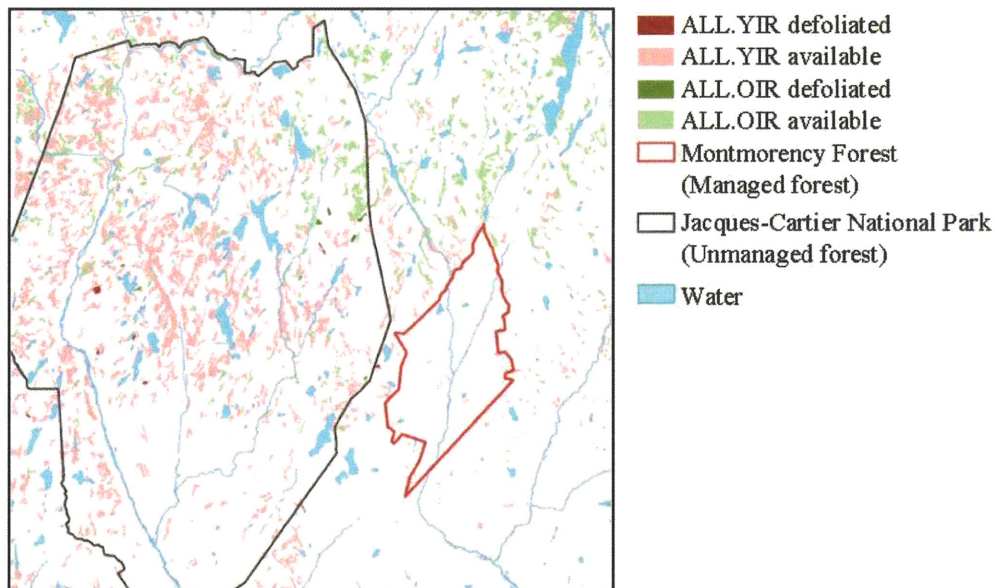

Figure 11: Map showing the spatial distribution of young and old irregular forest stands (5 types; see Figure 7) and their defoliation across the landscape in a 1600 km^2 in the LWR.
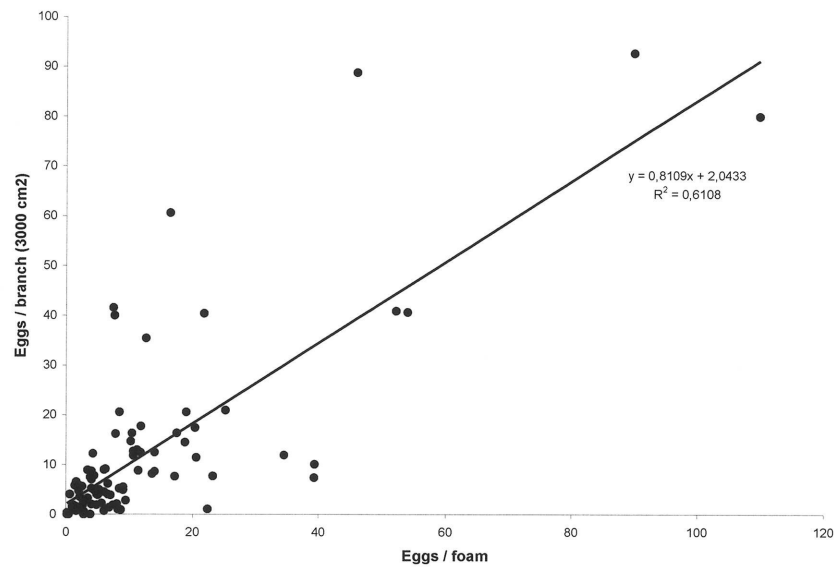
Figure 12: Correlation between egg population estimates from foam traps and those obtained from 1-m branches.
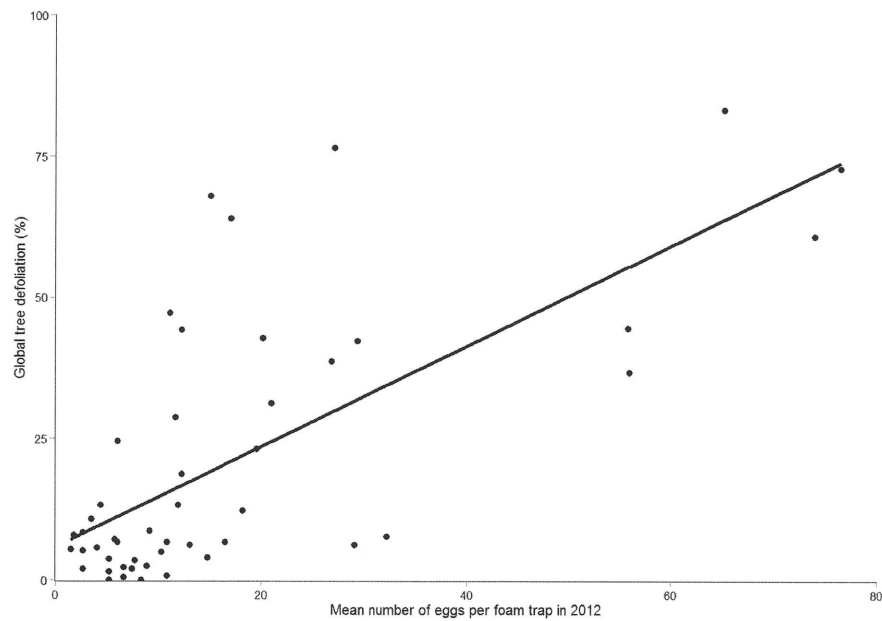

Figure 13: Relationship between the mean number of eggs/foam trap in fall 2012 and 2013 defoliation in balsam fir stands of the LWR.
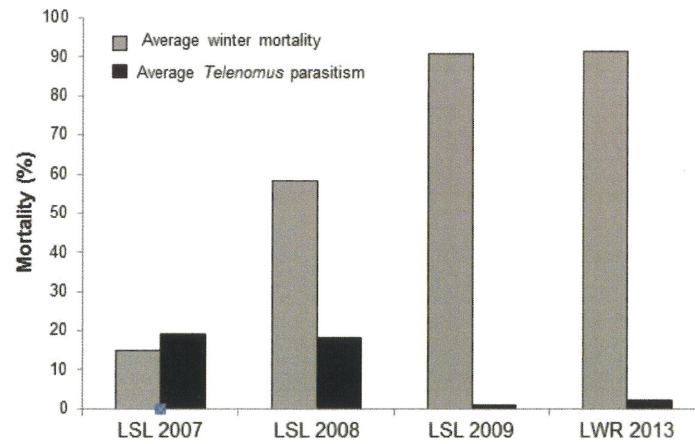
Figure 14: Egg mortality resulting from winter conditions and *Telenomus* parasitism in the Lower St Lawrence region between 2007 and 2009 and in the LWR in spring 2013.
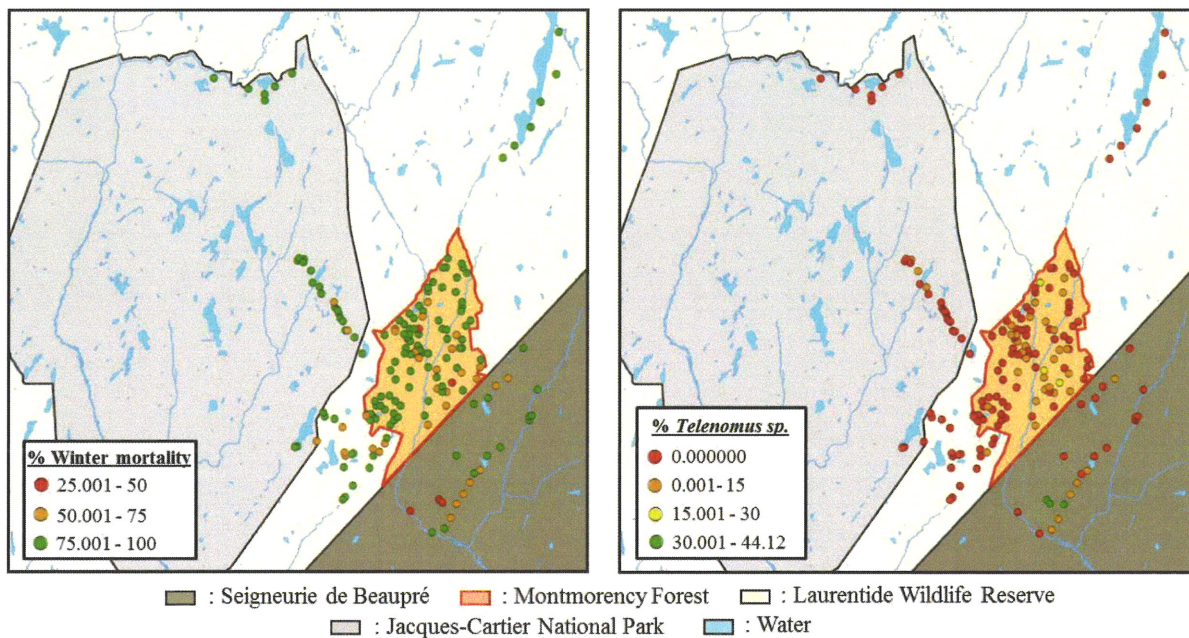

Figure 15 : HL egg mortality resulting from winter conditions and *Telenomus* parasitism in the plot network established in the LWR.
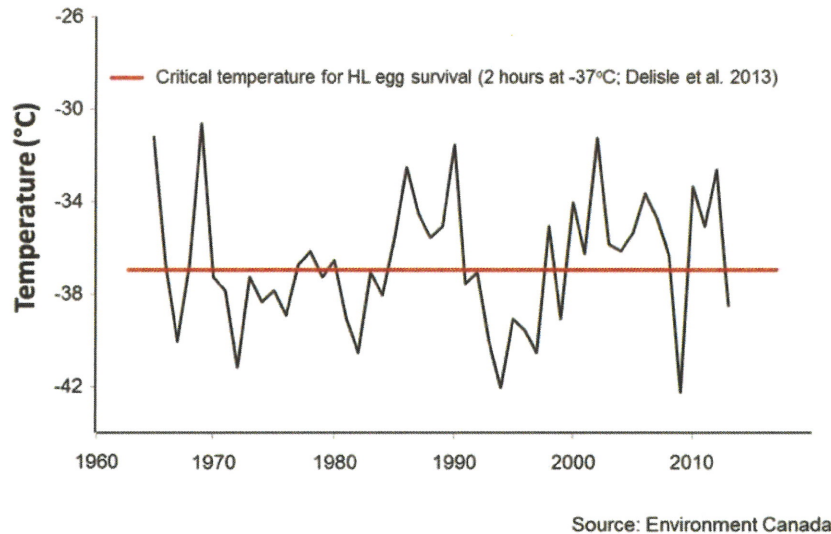
Source: Environment Canada

Figure 16: Lowest winter temperatures recorded at Montmorency Forest between 1965 and 2013 with respect to a critical temperature threshold for egg survival recently determined by Delisle et al. (2013).
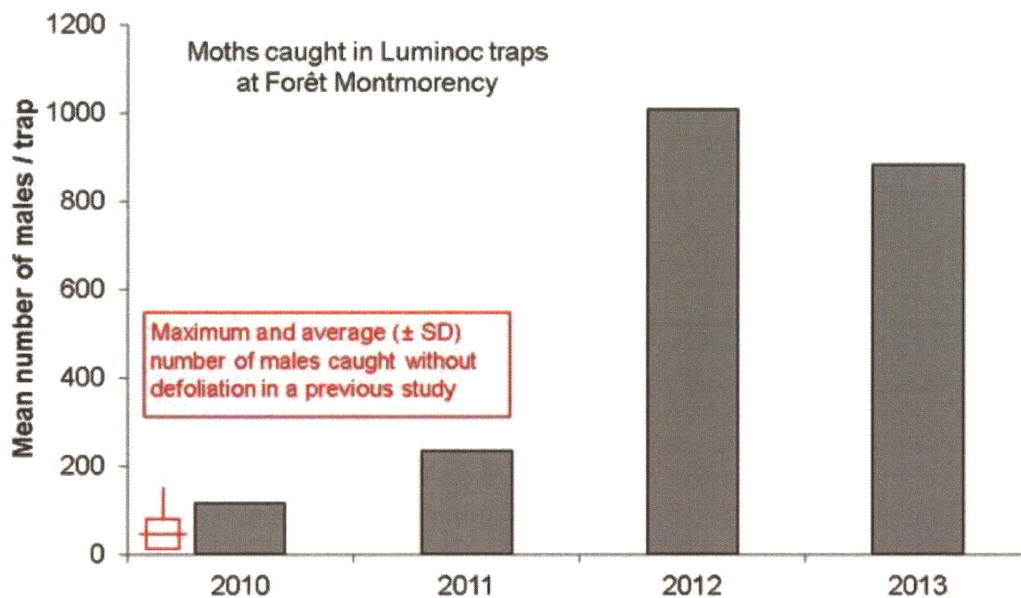

Figure 17: HL moth abundance measured with Luminoc® traps in Montmorency Forest between 2010 and 2013.

Table 1: Models for predicting HL defoliation on the basis of egg population estimates from foam traps and other variables.

Variables	Estimate ± Std. Error	df	F-statistic	R^2
Model no.1		46	43.37***	0.474
Intercept	5.802 ± 3.400			
Eggs.012	0.889 ± 0.135***			
Model no.2		45	27.04***	0.526
Intercept	7268.032 ± 2966.242*			
Eggs.012	0.888 ± 0.128***			
Latitude	-153.494 ± 62.694*			
Model no.3		45	28.87***	0.543
Intercept	41.809 ± 13.215**			
Eggs.012	0.965 ± 0.129***			
Wint.mor	-0.436 ± 0.155**			
Model no.4		43	21.08***	0.631
Intercept	0.000 ± 0.000*			
Eggs.012	0.959 ± 0.116***			
Latitude	-0.003 ± 0.001*			
Wint.mor	-0.002 ± 0.001*			
Latitude × Wint.mor	0.317 ± 0.125*			
Model no.5		25	28.68***	0.748
Intercept	1.496 ± 4.183			
Eggs.012	0.400 ± 0.251			
S.pupae	1.095 ± 1.772			
Eggs.012 × S.pupae	0.264 ± 0.106*			
Model no.6		23	25.99***	0.817
Intercept	337.409 ± 2755.872			
Eggs.012	288.670 ± 129.274*			
Latitude	-7.092 ± 58.241			
S.pupae	0.525 ± 1.538			
Eggs.012 × S.pupae	0.286 ± 0.091**			
Eggs.012 × Latitude	-6.093 ± 2.732*			

Eggs.012: mean number of eggs/foam trap in 2012; S.pupae: mean number of surviving pupae/pupation shelter; Wint.mor: % egg winter mortality;