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Subnivean Survival of Hemlock Woolly Adelgid (*Adelges tsugae*) in New England

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The hemlock woolly adelgid (*Adelges tsugae*) is a non-native insect from Japan that has become the most damaging pest of eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*Tsuga caroliniana*) in invaded areas of the eastern United States (Morin and Liebhold 2015). *Adelges tsugae* feeds on ray parenchyma cell contents (Young et al. 1995), which results in bud mortality, lack of shoot growth, dieback, foliage discoloration, premature needle loss, and eventual death. The pest has spread throughout most of the southern range of eastern hemlock and is currently invading northern New England, upstate New York, and Michigan, U.S. (USDA Forest Service 2016). While mortality has been devastating in the southern states, trees may survive for a decade or more in the north (Orwig and Foster 1998) as winter temperatures decrease *A. tsugae* survivorship (Parker et al. 1999). Snowpack is known to influence the survival of insects and small mammals by insulating them from low temperatures and moderating thermal fluctuations (Marchand 2014). High survivorship of *A. tsugae* has been observed in this subnivean zone (McClure and Cheah 2002; Cheah 2016), and the objective here was to quantify its survival in this refuge.

This study was devised during the cold and snowy winter of 2010/2011 in New England. Ten *A. tsugae*-infested eastern hemlock trees in South Hadley, Massachusetts, U.S. (Lat. 42.289672°, Long. -72.600048°, Elev. 75 m) were found that had lower limbs pinned to the ground by heavy snow, and subsequently buried by following snowstorms. The limbs that were buried in snow were marked with surveyor flags. Four trees were selected in the same way in Brattleboro, Vermont, U.S. (Lat. 42.835048°, Long. -72.553940°, Elev. 85 m).

After the snow melted in March, one 50 cm long branch sample per tree was collected from the distal portion of the limb that was buried in snow and was observed to have high *A. tsugae* density. One 50 cm distal branch sample per tree that was above the snow, between 4.6–6.1 m, and with high *A. tsugae* densities was sampled using a pole pruner. One-year-old shoots were cut from the branches and placed into brown paper bags. Shoots were randomly sub-sampled from the paper bags until approximately 100 *A. tsugae* per branch were assessed for survival.

The numbers of live and dead sistens (overwintering generation) *A. tsugae* nymphs were counted on each shoot under a dissecting microscope (10–20×). First instars were excluded, as they would have died during summer–autumn due to factors other than winter temperatures. Nymphs were considered dead if the body was desiccated or the hemolymph was cloudy brown or black when pierced with a bent teasing needle. They were considered live if the body was normal shaped, rebounded to the touch, and had purple-colored hemolymph when pierced. The length of the examined shoots (mm) was measured to calculate *A. tsugae* density for each branch. Furthermore, the number of elongate hemlock scale (*Fiorinia externa*) insects and the total number of needles were counted on each shoot to calculate their density per needle, but survivorship was not assessed. Data were analyzed by paired samples t-tests using SPSS v.16 and presented as means ± standard error. Percent survivorship was arcsine square root transformed. Temperature and snow data from the weather station nearest to each site was acquired from Amherst, Massachusetts, U.S. (12 km from South Hadley) and Keene, New Hampshire, U.S. (24 km from Brattleboro) (Northeast Regional Climate Center 2016).

The South Hadley, MA site had 989 adelgids assessed for winter survivorship above the snow and 1019 below the snow, and the Brattleboro, VT site had 405 adelgids assessed above the snow and 410 below the snow. Survivorship of *A. tsugae* was significantly higher when buried beneath the snowpack compared to above the snowpack at South Hadley ($t_{0.05(2)9} = -10.5$, $P < 0.0001$) and Brattleboro ($t_{0.05(2)3} = 5.8$, $P = 0.01$) (Table 1). There were no differences in *A. tsugae* density and *F. externa* density above and below the snowpack at either South Hadley (*A. tsugae* density, $t_{0.05(2)9} = 1.6$, $P = 0.1$; *F. externa* density, $t_{0.05(2)9} = -1.2$, $P = 0.2$) or Brattleboro (*A. tsugae* density, $t_{0.05(2)3} = 0.1$, $P = 0.9$; *F. externa* density, $t_{0.05(2)3} = 1.7$, $P = 0.2$). The weather was colder at the more northerly Brattleboro site. For example, on 25 January 2011, ambient temperatures reached -23.9°C in South Hadley and -28.9°C in Brattleboro, while there was a deep snowpack. At Brattleboro, 99.8% of exposed *A. tsugae* died, but only 56.8% of snow covered ones died.

Because of snow, *A. tsugae* may be capable of invading farther north than estimates, based on ambient air temperature, as hypothesized for temperature-moderated hemlock stands (Lishawa et al. 2007). Furthermore, in the northern range of *A. tsugae* or at high elevations, survival below the snowpack results in an important source population to re-infest trees after high winter mortality. Re-infestation could then happen at a faster rate than would occur otherwise from the few survivors above the snowpack and from passive wind and avian dispersal. This knowledge can be applied immediately to assist in the integrated pest management of *A. tsugae* on high-value trees. Pruning lower branches to eliminate their burial under snow would reduce local *A. tsugae* populations during cold winters, potentially slow the re-infestation of the tree, and allow for tree vigor to be maintained or recover. Pruning could work

Table 1. *Adelges tsugae* survivorship, *A. tsugae* density, and *Fiorinia externa* density on eastern hemlock tree branches above the snowpack and buried below the snowpack in South Hadley, MA (n = 10) and Brattleboro, VT (n = 4) and winter weather data from December 2010 to February 2011. Treatments with the same letter by column are not significantly different, paired t-test (α = 0.05).

	Study site	
	South Hadley, MA	Brattleboro, VT
A. tsugae survivorship (%)		
Above snowpack	5.21 ± 1.48 a	0.24 ± 0.24 a
Below snowpack	62.37 ± 4.59 b	43.20 ± 9.73 b
A. tsugae density (No./cm)		
Above snowpack	4.2 ± 0.53 a	4.2 ± 0.33 a
Below snowpack	3.5 ± 0.41 a	4.4 ± 1.20 a
F. externa density (No./needle)		
Above snowpack	0.054 ± 0.019 a	0.0015 ± 0.00089 a
Below snowpack	0.093 ± 0.026 a	0 ± 0 a
Winter weather summary		
December 2010		
Avg. min temp. (°C)	-7.5	-8.6
Min. temp. (°C)	-15.0	-16.7
Snowpack depth (cm)	16.2	10.2
January 2011		
Avg. min temp. (°C)	-13.4	-14.0
Min. temp. (°C)	-23.9	-28.9
Snowpack depth (cm)	80.5	81.3
February 2011		
Avg. min temp. (°C)	-12.3	-14.4
Min. temp. (°C)	-22.8	-25.0
Snowpack depth (cm)	52.1	76.2

in concert with chemical control (Webb et al. 2003) to protect trees in cold climates, but may only be practical for homeowners, or within parks, campuses, small woodlots, and urban forests.

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