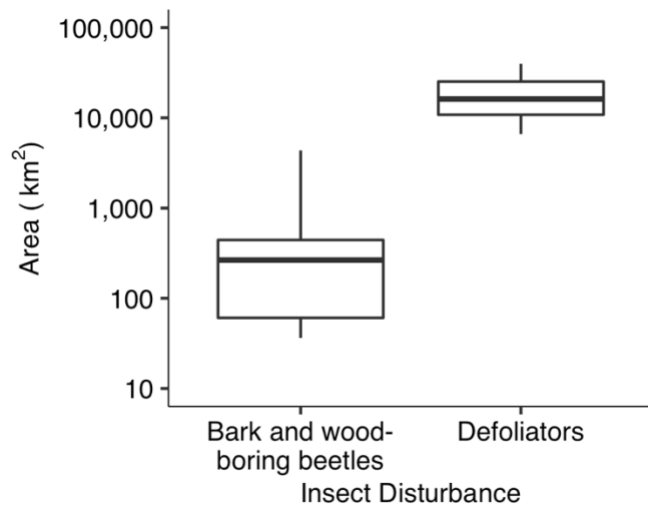


1 *Supplementary Figures*



2

3 Supplementary Figure 1. Defoliating insect species annually covered 23-times the area of

4 all bark and wood-boring beetles combined within our 439,661 km² study area. The area

5 disturbed by defoliators and bark/wood-boring beetles was calculated using aerial surveys

6 from Natural Resources Canada – Canadian Forest Service (CFS) and the Ontario Ministry

7 of Natural Resources and Forestry (OMNRF). Solid lines show medians, boxes show inter-

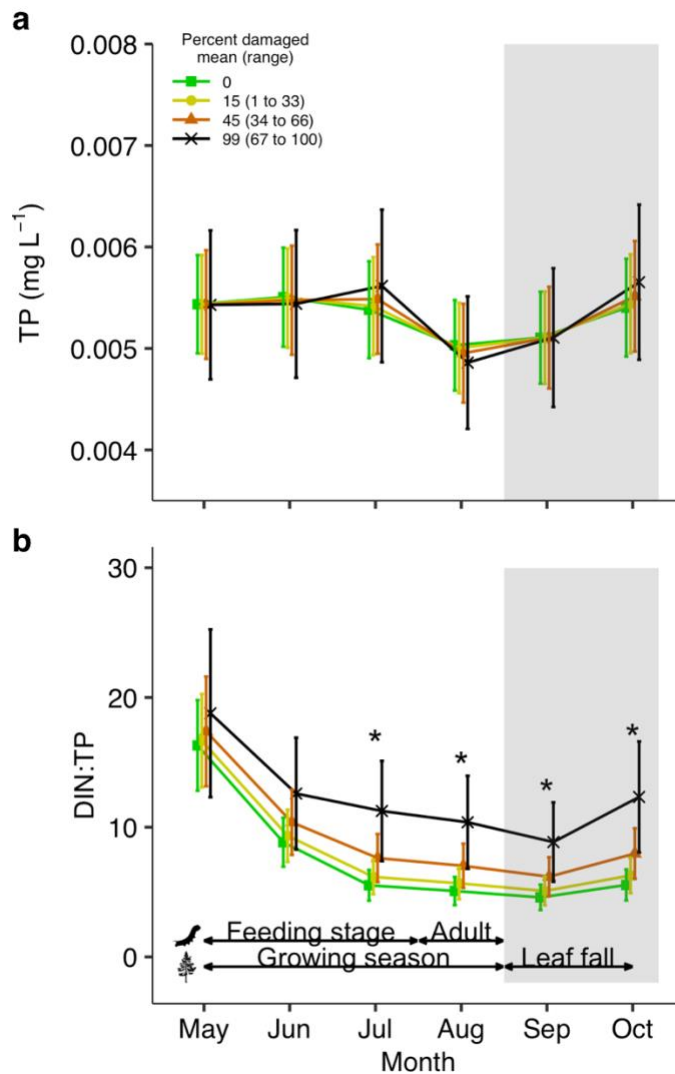
8 quartile range, and whiskers show 1.5-times the interquartile range. A paired two-sided t-

9 test was used to compare the mean difference in the annual area covered between the two

10 groups from 2004 to 2016 ($t_{12} = -8.00$, $p < 0.001$). Data from 2004 to 2016 were used as this

11 was when both defoliators and bark/wood-boring beetle disturbances were present in the

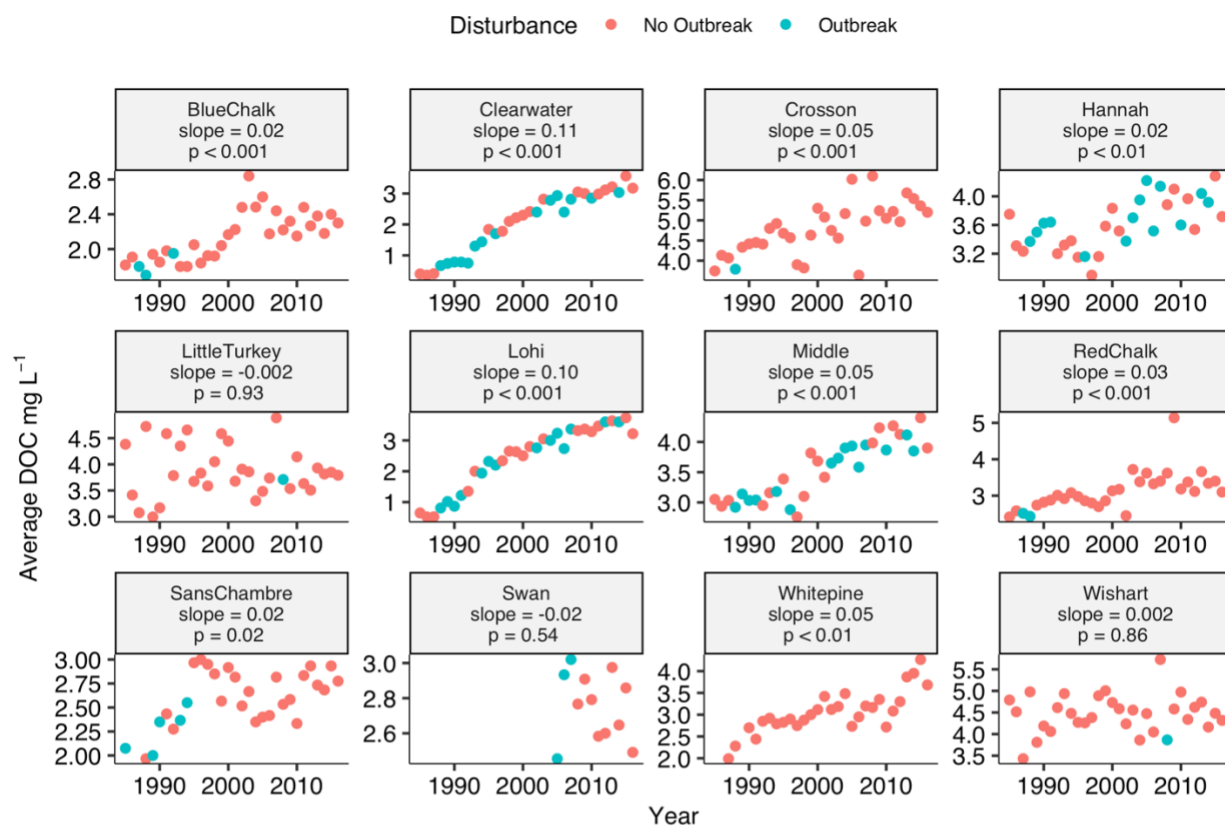
12 region.



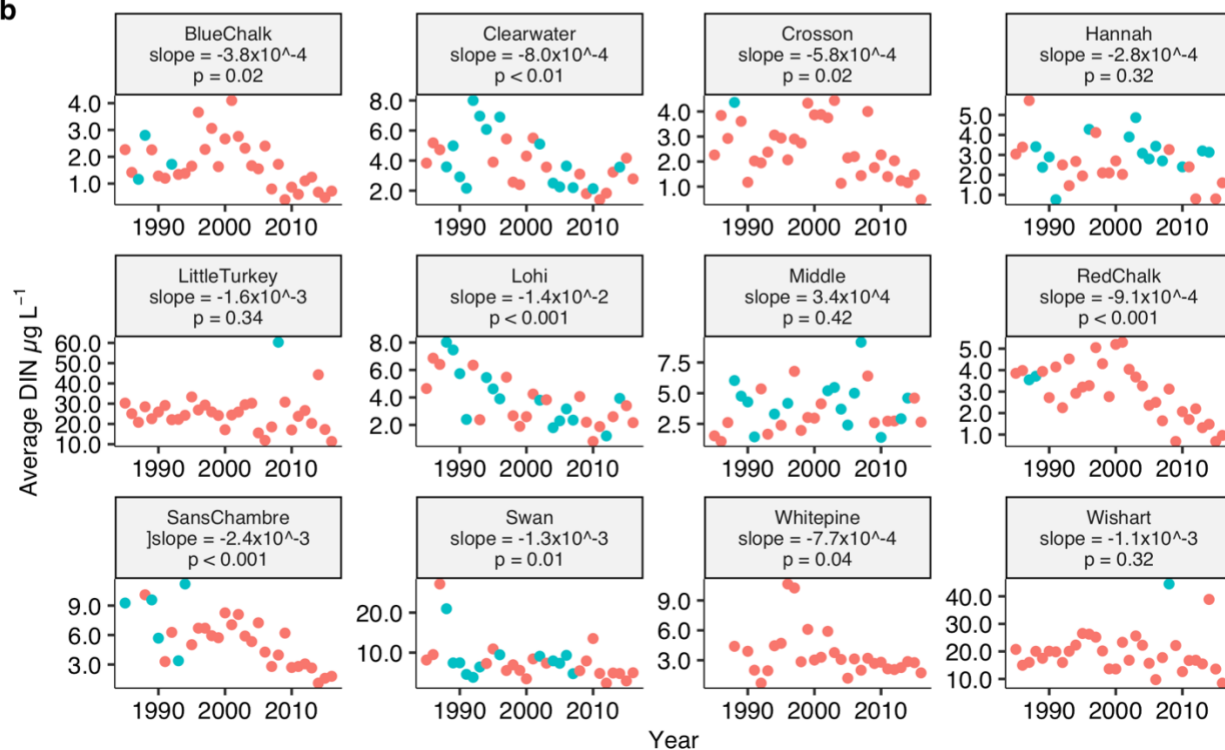
Supplementary Figure 2. Total phosphorus (TP) changed little during insect outbreaks. Mean ($\pm$ 95% CI) monthly (a) TP and (b) DIN:TP ratio in lake water averaged across 12 lakes from 1985 to 2016. For visualization purposes, monthly catchment-level averages of TP and DIN:TP were grouped into three equal-width bins for the percent catchment area defoliated and points show corresponding mean $\pm$ SE. However, slopes were estimated to models fitted to non-binned data with $N = 296$ to 358 and 240 to 312 per month for TP and DIN:TP, respectively (Supplementary Table 2). TP did not change with insects (mean 95% CI across months = <-0.01 to <0.01) but DIN:TP ratio increased during outbreaks in

22 later months (mean 95% CI across months = 0.16 to 1.27). Upper arrows in (b) are the
23 typical life cycle stages of defoliating insects while lower arrows indicate typical tree
24 phenology. Shaded area represents typical period of leaf senescence. Asterisks (*) denotes
25 a statistically significant effect of the percentage of catchment damage on monthly
26 DIN:TP within a given month calculated using estimated marginal means (see
27 Supplementary Table 2). Conditional $R_c^2 = 0.41$ and 0.57 in (a) and (b), respectively.
28

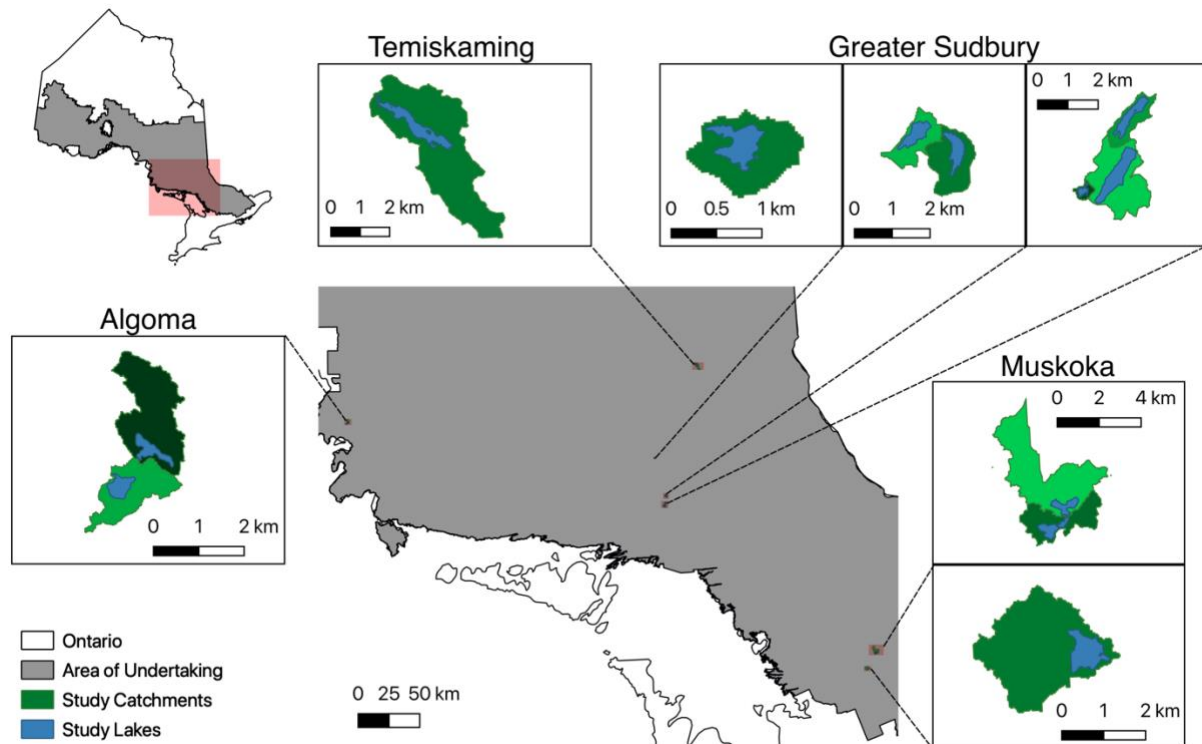
a



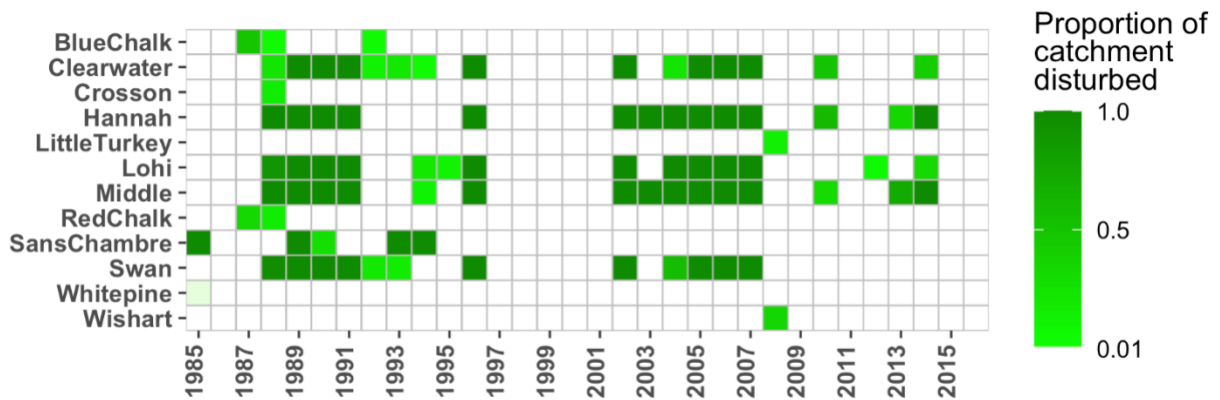
b



Supplementary Figure 3. Temporal trends in water chemistry in the 12 study lakes from 1985 to 2016. Average ice-free (May to October) (a) DOC concentrations increased while (b) DIN concentrations decreased. Theil-Sen's slopes and p values represent the rate of change and significance in (a) DOC (mg L^{-1}) or (b) DIN ($\mu\text{g L}^{-1}$) for each catchment. Blue points indicate years with outbreaks while red represents no outbreaks.



Supplementary Figure 4. Map of study catchments within our study area. The grey area represents the Area of Undertaking, where insect outbreaks were surveyed by Natural Resources Canada – Canadian Forest Service (CFS) and the Ontario Ministry of Natural Resources and Forestry (OMNRF). Catchments are denoted in green with different shades used when two or more catchments are adjoined (for visualisation).



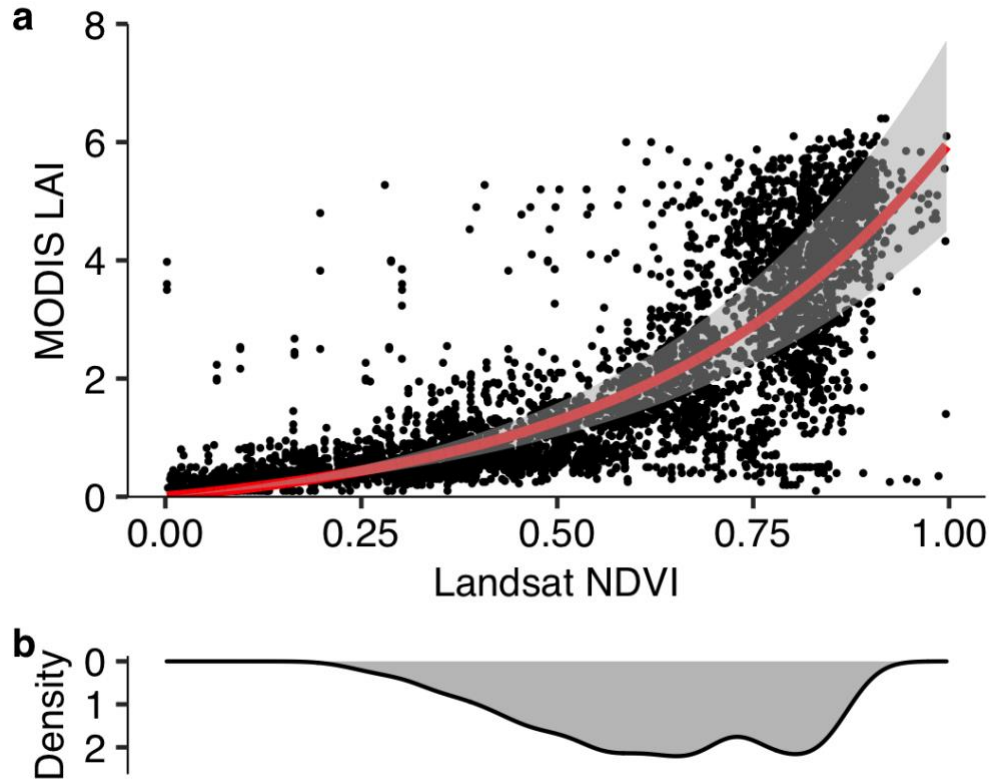
51

52 Supplementary Figure 5. History of insect outbreaks within each catchment. Green tiles

53 represent the proportion of catchment disturbed while white tiles show years where no

54 outbreaks occurred.

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57 Supplementary Figure 6. Prediction of LAI from NDVI in 2016. (a) Correlation between
 58 Landsat NDVI and MODIS LAI across pixels on 23 imaging dates in our 11 study
 59 catchments (total $n = 5865$). 30 m^2 NDVI pixels from January to December 2016 were
 60 rescaled to match 500 m^2 LAI pixels. The red line in (a) represents the mean ($\pm 95\%$ CI) fit
 61 between NDVI and LAI: $\text{LAI} = 0.48 \times (e^{2.6 \times \text{NDVI}} - 1)$. (b) Probability distribution of NDVI
 62 values in our catchments.

Supplementary Table 1. Overall model summary outputs for the effects of insect damage, month, and forest cover on LAI, DOC and DIN across our 12 study catchments/lakes. All continuous independent variables were scaled to a mean of zero and standard deviation of one to compare effect sizes. Model estimates and 95% confidence intervals (in parentheses) are displayed along with the associated p-values. Significant p-values indicate a statistical difference from the model intercept.

<i>Predictors</i>	LAI		DOC		log(DIN)	
	<i>Estimates</i>	<i>p</i>	<i>Estimates</i>	<i>p</i>	<i>Estimates</i>	<i>p</i>
Intercept	1.69 (1.54 – 1.84)	<0.001	2.92 (2.44 – 3.40)	<0.001	-2.42 (-2.86 – -1.98)	<0.001
Percent Disturbed	-0.06 (-0.16 – 0.03)	0.208	-0.17 (-0.35 – 0.02)	0.074	0.06 (-0.12 – 0.24)	0.501
Month [Jun]	1.15 (1.11 – 1.19)	<0.001	0.18 (0.11 – 0.25)	<0.001	-0.56 (-0.64 – -0.47)	<0.001
Month [Jul]	1.30 (1.25 – 1.35)	<0.001	0.31 (0.22 – 0.40)	<0.001	-0.97 (-1.07 – -0.87)	<0.001
Month [Aug]	1.07 (1.01 – 1.13)	<0.001	0.27 (0.17 – 0.37)	<0.001	-1.15 (-1.26 – -1.05)	<0.001
Month [Sep]	0.03 (-0.03 – 0.09)	0.349	0.30 (0.19 – 0.40)	<0.001	-1.23 (-1.34 – -1.12)	<0.001
Month [Oct]	-0.69 (-0.75 – -0.63)	<0.001	0.29 (0.18 – 0.40)	<0.001	-0.96 (-1.07 – -0.84)	<0.001

Proportion deciduous trees	0.36 (0.19 – 0.54)	0.001	0.32 (-0.26 – 0.90)	0.246	0.42 (-0.11 – 0.95)	0.108
Proportion coniferous trees	0.21 (0.04 – 0.39)	0.022	0.07 (-0.50 – 0.64)	0.791	-0.03 (-0.47 – 0.42)	0.901
Percent disturbed × Month [Jun]	-0.19 (-0.23 – -0.15)	<0.001	0.02 (-0.05 – 0.09)	0.613	0.06 (-0.02 – 0.15)	0.134
Percent disturbed × Month [Jul]	-0.20 (-0.25 – -0.14)	<0.001	-0.08 (-0.17 – 0.01)	0.075	0.20 (0.10 – 0.30)	<0.001
Percent disturbed × Month [Aug]	-0.12 (-0.18 – -0.06)	<0.001	-0.05 (-0.15 – 0.05)	0.304	0.20 (0.09 – 0.31)	<0.001
Percent disturbed × Month [Sep]	0.05 (-0.01 – 0.11)	0.120	-0.11 (-0.21 – -0.01)	0.038	0.18 (0.07 – 0.29)	0.001
Percent disturbed × Month [Oct]	0.11 (0.04 – 0.17)	0.001	-0.09 (-0.20 – 0.02)	0.117	0.24 (0.12 – 0.35)	<0.001
Percent disturbed × Proportion deciduous	-0.02 (-0.13 – 0.09)	0.740	-0.24 (-0.45 – -0.03)	0.028	0.09 (-0.09 – 0.27)	0.306
Percent disturbed × Proportion coniferous	-0.04 (-0.14 – 0.06)	0.460	0.05 (-0.20 – 0.30)	0.717	0.02 (-0.13 – 0.16)	0.832
Observations	2154		1803		1659	

Supplementary Table 2. Within-month effects of percentage of catchment damaged on LAI, DOC, DIN, TP, and DIN:TP. Values were computed using the *emmeans* package in R. Modelled estimates and 95% confidence intervals (in parentheses) are displayed along with associated p-values. Bolded p-values indicate statistically significant effects, i.e., different from zero.

Month	LAI		DOC (mg L ⁻¹)		DIN (mg L ⁻¹)		TP (mg L ⁻¹)		DIN:TP	
	Estimates	p	Estimates	p	Estimates	p	Estimates	p	Estimates	p
May	-0.18 (-0.46 – 0.10)	0.208	-0.48 (-1.00 – 0.04)	0.071	0.17 (-0.33 – 0.67)	0.501	-0.001 (-0.22 – 0.21)	0.992	0.14 (-0.42 – 0.69)	0.623
June	-0.71 (-0.99 – -0.43)	<0.001	-0.44 (-0.95 – 0.08)	0.096	0.35 (-0.15 – 0.85)	0.166	-0.01 (-0.22 – 0.20)	0.909	0.34 (-0.21 – 0.89)	0.222
July	-0.74 (-1.02 – -0.46)	<0.001	-0.72 (-1.24 – -0.21)	0.006	0.73 (0.24 – 1.23)	0.004	0.04 (-0.17 – 0.25)	0.687	0.72 (0.17 – 1.27)	0.010
Aug	-0.52 (-0.80 – -0.24)	<0.001	-0.64 (-1.16 – -0.12)	0.015	0.73 (0.23 – 1.24)	0.004	-0.03 (-0.25 – 0.40)	0.745	0.71 (0.16 – 1.27)	0.012
Sep	-0.05 (-0.31 – 0.24)	0.753	-0.85 (-1.37 – -0.33)	0.001	0.68 (0.18 – 1.19)	0.008	0.0002 (-0.21 – 0.21)	0.998	0.65 (0.09 – 1.20)	0.023
Oct	0.12 (-0.16 – 0.40)	0.390	-0.74 (-1.26 – -0.22)	0.005	0.85 (0.34 – 1.36)	0.001	0.05 (-0.17 – 0.26)	0.673	0.77 (0.21 – 1.33)	0.008

73 Supplementary Table 3. Summary of study lakes. Asterisk (*) denotes lake that is not
 74 thermally stratified.

Region	Lake	Latitude (°)	Longitude (°)	Lake Area (ha)	Max depth (m)	Catchment Area (ha)
Algoma	Little Turkey	47.04227	-84.40812	19.85	13.0	134
Algoma	Wishart*	47.04948	-84.39924	19.09	4.5	245
Greater Sudbury	Clearwater	46.37042	-81.05045	77.02	21.5	285
Greater Sudbury	Hannah	46.44328	-81.03831	27.80	8.0	83
Greater Sudbury	Lohi	46.38749	-81.04330	41.15	19.0	83
Greater Sudbury	Middle Sans	46.43897	-81.02482	28.98	12.0	132
Greater Sudbury	Chambre	46.72141	-81.13066	15.72	17.5	62
Greater Sudbury	Swan	46.36602	-81.06544	7.48	8.8	18
Muskoka	Blue Chalk	45.19917	-78.93835	49.55	22.0	1045
Muskoka	Crosson	45.08356	-79.03645	54.96	26.0	508
Muskoka	Red Chalk	45.18981	-78.94753	55.10	32.0	381
Temiskaming	Whitepine	47.38400	-80.63133	87.24	59.0	911

75

76

77 Supplementary Table 4. Summary of defoliating insect surveyed by CFS and OMNRF.

78 Bolded species were present in our 12 lake catchments. Outbreaks were defined as $\geq 50\%$

79 of the catchment affected.

Common Name	Species Name	Years With Recorded Outbreaks	Unique Catchments Affected
Forest Tent Caterpillar	<i>Malacosoma disstria</i>	1948-57, 1961-2018	55097
Spruce Budworm	<i>Choristoneura fumiferana</i>	1941-63, 1967-2018	53667
Jack Pine Budworm	<i>Choristoneura pinus</i>	1937-1942, 1945-48, 1954, 1961-62, 1967-73, 1983-97, 2003-12, 2015-18	22391
Birch Skeletonizer	<i>Bucculatrix canadensisella</i>	2002, 2005, 2012	14677
Aspen Twoleaf Tier	<i>Enargia decolor</i>	1997-96, 2005-06, 2010-14	8370
Large Aspen Tortrix	<i>Choristoneura conflictana</i>	1996-2002, 2004-12, 2016-18	3472
Gypsy Moth	<i>Lymantria dispar dispar</i>	1981-96, 1999-2004, 2006, 2008, 2012-14	2675
Bruce Spanworm	<i>Operophtera bruceata</i>	1998, 2000, 2002-03, 2008-10	850
Poplar Serpentine Leafminer	<i>Phyllocnistis populiella</i>	1997	318
Larch Casebearer	<i>Coleophora laricella</i>	2002-07, 2009-17	238
Cedar Leafminer	<i>Argyresthia canadensis</i>	2003, 2005, 2007, 2010-12, 2014-15, 2017-18	228
Unknown Aspen Leafroller	NA	2007, 2010	185
Early Aspen Leafroller	<i>Pseudexentera oregonana</i>	2008, 2011	162
Maple Leafcutter	<i>Paraclemensia acerifoliella</i>	2004-05	109
Hemlock Looper	<i>Lambdina fiscellaria</i>	2001-2005	100
Oak Defoliators Complex	<i>Croesia semipurpurana</i> , <i>Choristoneura rosaceana</i>	2007, 2009	75
Poplar Flea Beetle	<i>Altica populi</i>	2002, 2005	61
Introduced Pine Sawfly	<i>Diprion similis</i>	2000	37
Redhumped Oakworm	<i>Symmerista canicosta</i>	2004-05	22
Birch Leafminer	<i>Fenusa pusilla</i>	2002, 2013	12
Other Insect	NA	2013, 2016, 2018	9
Birch Casebearer	<i>Coleophora serratella</i>	2012	4
Oak Leaf Roller	<i>Argyrotaenia quercifoliana</i>	2006	4

Pine False Webworm	<i>Acantholyda erythrocephala</i>	2009-13, 2015, 2017	4
Pink-striped Oakworm	<i>Anisota virginiensis</i>	2009-10, 2012	4
Fall Cankerworm	<i>Alsophila pometaria</i>	2002	2
Fall Webworm	<i>Hyphantria cunea</i>	2016	1
Satin Moth	<i>Leucoma salicis</i>	2018	1

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