Effects of Agricultural Intensity Vary across Anuran Species

by

Alex Koumaris

A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial
fulfillment of the requirements for the degree of

Master of Science

in

Biology

Carleton University

Ottawa, Ontario

© 2015, Alex Koumaris

Note: I've used the "we" pronoun in lieu of "I" in my thesis because, although I was responsible for conducting this research and writing each draft, Dr. Fahrig's ideas and edits have been incorporated throughout. Dr. Fahrig also provided guidance for proposing, planning, and writing this paper.

Abstract

Studies on the effects of agricultural intensity on anurans have found inconsistent results both between and within species, with varying conclusions about what could be driving these effects. One possible explanation for this variation is that agricultural intensity can be correlated with adult habitat amount. Another possible explanation is that differences in tadpole life history or sensitivity to agrochemical toxicity, may cause different responses to agricultural intensity because of its effects on larval habitat quality. We identified 39 ponds in Eastern Ontario, surrounded by a wide variation of row crop cover, where we measured anuran abundances, nitrate concentration, and a suite of local pond variables. We then constructed path analyses for each species to determine the direction and potential causes of effect of agricultural intensity on abundance. We found variable responses to agricultural intensity across anurans. As predicted, much of this variation could be explained by adult habitat amount and larval habitat quality. Overall, our results suggest that agricultural intensity itself is not strongly affecting anurans in our region, but confirm that habitat loss due to agriculture is particularly detrimental for forest species. We suggest that, since the term 'agricultural intensity' is used inconsistently in the literature, it should only refer to effects of increased chemical usage (i.e. for a particular crop type), independent of habitat amount.

Acknowledgements

I could not have written this thesis without considerable guidance from Dr. Lenore Fahrig, for which I am very grateful. Thank you for your mentorship and for making your lab such an exceptionally warm environment. I also appreciate the extra steps you take to keep us well-versed in landscape ecology and to ensure the overall sense of community at the lab.

I would also like to thank the members of my committee, Dr. Gabriel Blouin-Demers and Dr. Steven J. Cooke, for providing constructive feedback during meetings.

It has been a pleasure working with the members of GLEL. I respect and appreciate the unique ability of our lab to maintain optimism and hope while discussing sometimes disheartening subjects in conservation biology. I would like to especially thank Sara Collins, Sandra Martins de Freitas, Amanda Martin, Liv Monck-Whipp, Tom Hotte, Susie Crowe, and Dr. Jude Girard for your helpful suggestions. I would also like to thank Pauline, Sheldon, Genevieve, Poliana, Fernanda, and Ludmila for your support.

I am very grateful for the assistance I received in the field and the lab from Chris Love, whose eternal enthusiasm kept work fun. Chris was the epitome of a great field assistant. I would also like to thank all of the field work volunteers, particularly Sarah Richardson, for your help in the early stages of field work, as well as the farm landowners, without whom this project would not have been possible.

Last, but certainly not least, I thank my friends and family for your support.

Table of Contents

Abstract	ii
Acknowledgements	iii
List of Tables	vi
List of Figures	vii
List of Appendices	viii
Introduction	1
Methods	
<i>Overview</i>	<i>5</i>
<i>Site selection</i>	<i>6</i>
<i>Anuran call surveys</i>	<i>7</i>
<i>Local Pond Variables</i>	<i>8</i>
<i>Landscape Variables</i>	<i>9</i>
<i>Data Analyses.....</i>	<i>9</i>
Scales of effect	9
Larval habitat quality	10
Path Analyses	10
Results	11
<i>Species responses to agricultural intensity</i>	<i>13</i>
Discussion	13
<i>What drives the differences between anurans species in their responses to agricultural intensity?</i>	<i>14</i>
<i>Study limitations</i>	<i>16</i>

<i>Implications</i>	18
<i>Agricultural intensity</i>	19
Tables	21
Figures	43
References	46
Appendices	
<i>Appendix 1</i>	60
<i>Appendix 2</i>	61
<i>Appendix 3</i>	62
<i>Appendix 4</i>	68
<i>Appendix 5</i>	75
<i>Appendix 6</i>	79
<i>Appendix 7</i>	80
<i>Appendix 8</i>	81
<i>Appendix 9</i>	82
<i>Appendix 10</i>	85
<i>Appendix 11</i>	86
<i>Appendix 12</i>	87

List of Tables

Table 1. Landscape studies examining the effects of proportion of agricultural land cover on anurans. Response variables included anuran abundance, species richness, and reproductive success	28
Table 2. Experimental studies on the effects of nitrate on anuran survivorship and/or growth. Only studies that conducted quantitative analyses were included. Response variables included tadpole relative growth rate, survivorship, or change in mass after a given amount of time, depending on the study	33
Table 3. Life history characteristics of anurans in eastern Ontario	40
Table 4. Pearson correlations for potential landscape predictors (measured as percent cover) in 250, 500 and 1000 m - radius landscapes. Significant correlations $p < 0.05$ are denoted by * and $p < 0.01$ by **. Low-intensity agricultural cover consisted of perennial crops, while high-intensity agricultural cover consisted of row crops. The other two predictors were forest cover and wetland cover in the landscapes	40
Table 5. Pearson correlation values for correlations between potential local habitat predictors of anuran abundance in 39 sample ponds in the agricultural region of Eastern Ontario. Boldness indicates absolute Pearson correlation values > 0.3 . Significant correlations of $p < 0.05$ are denoted by *, $p < 0.01$ by **	45
Table 6. Pearson correlations between anuran abundance and local pond predictors in 39 sample ponds in the agricultural region of Eastern Ontario. Boldness indicates the highest absolute Pearson correlation value for each species. Significant correlations of $p < 0.05$ are denoted by (*), $p < 0.01$ by (**).	48
Table 7. Path analysis model fit criteria and path coefficients. Several goodness of fit measures were included to assess the overall fit of each model, with boldness indicating a "good fit". Measures included: the χ^2 "badness of fit" measure (if $p < 0.05$, the model was a bad fit (Hair et al., 2006)), the comparative fit index (if $CFI \geq 0.90$, the model was a good fit (Bentler, 1990)), the Tucker-Lewis index (if $TLI > 0.95$, the model was a good fit (Bollen, 1989)), and root mean square error (if $RMSEA \leq 0.07$, the model was a good fit (Hu & Bentler, 1999))	49

List of Figures

- Figure 1.** Distribution of ponds sampled for anurans with call surveys, in the agricultural region of Eastern Ontario (n = 39). Each pond is represented by a circle with shading indicating percent high-intensity agricultural land cover (row crops) within 500 m of the pond. Other areas of high-intensity agricultural land cover on the map are represented by green, while areas of low intensity agricultural land cover (perennial crops) are represented by yellow 50
- Figure 2.** The proportion of 39 study ponds in the agricultural region of Eastern Ontario at which anurans were found during call surveys (4 surveys per pond) on nights from April 15th until July 29th, 2013 51
- Figure 3.** Path analyses assessing the direction and potential causes of effect of agricultural intensity on the abundance of anurans in the agricultural region of Eastern Ontario. Predictor variables for a given species included nitrate concentration (ni), the best measure of larval habitat quality for that species (% emergent vegetation pond cover (em), water temperature (wt), or pH), and the proportion of landscapes in each of the following: high-intensity row crop cover (hi), adult habitat for that species (forest (fo) or low-intensity perennial crop cover (lo)) , and wetland cover (we). The scales at which each landscape effect was strongest for each species were 250, 500, or 1000 m and were displayed with each cover type (e.g. for we500, the effects of wetlands were strongest at 500 m). Error terms (residual variance) for abundance and nitrate are denoted by 'e' 52

List of Appendices

Appendix 1. Generalized linear model output for effects of landscape predictors on anuran abundance (8 sp) in Eastern Ontario (39 ponds), in which β -coefficient values are displayed at 6 scales: 100, 250, 500, and 1000, 2000, and 4000 m. Only 250, 500, and 1000 m scales were considered for later analyses because of high landscape predictor correlations between crop cover and habitat at other scales.....	60
Appendix 2. Proportion of landscape cover types at all scales surrounding ponds (39) in the agricultural region of Eastern Ontario. Low-intensity agricultural cover (lo) consisted mostly of perennial crops, while high-intensity agricultural cover (hi) consisted of row crops. The other two landscape predictors were forest (fo) and wetland (we) cover.....	61
Appendix 3. Raw pond data (2013 data). All values were averaged across 4 surveys. See methods section for more information	62
Appendix 4. Raw call survey data for the abundance of each anuran taken with 10-minute chorus. We used the following abundance classes: 0 (no calls), 1 (distinct calls of separate individuals), 2 (some calls overlap but most individuals can still be identified), 3 (mostly overlapping calls and continuous calling) (see methods for more information). Estimated actual abundance was also noted in parentheses, but we did not use this data because we felt it was less reliable than ranks.....	68
Appendix 5. Raw landscape predictor data for landscapes surrounding Eastern Ontario ponds across 6 scales. Low-intensity agricultural cover (lo) consisted of perennial crops, while high-intensity agricultural cover (hi) consisted of row crops. The other two predictors were forest cover (fo) and wetland cover (we) in the landscapes. (e.g. 'fo100' denotes forest cover within 100 m of the pond).....	75
Appendix 6. Pearson correlations for potential landscape predictors (measured as percent cover) in 100, 250, 500, 1000, 2000, and 4000 m - radius landscapes. Significant correlations $p < 0.05$ are denoted by * and $p < 0.01$ by **. Low-intensity agricultural cover (lo) consisted of perennial crops, while high-intensity agricultural cover (hi) consisted of row crops. The other two predictors were forest cover (fo) and wetland cover(we) in the landscapes	79
Appendix 7. Pearson correlation values for correlations between potential landscape predictors and local habitat predictors of anuran abundance in 39 sample ponds in the agricultural region of Eastern Ontario. Low-intensity agricultural cover (lo) consisted of perennial crops, while high-intensity agricultural cover (hi) consisted of row crops. The other two predictors were forest cover (fo) and wetland cover(we) in the landscapes. Boldness indicates absolute Pearson correlation values ≥ 0.3 . Significant correlations of $p < 0.05$ are denoted by *, $p < 0.01$ by **	80

Appendix 8. The Cadmium Reduction Method for determining nitrate concentration (see APHA, 1998)	81
Appendix 9. Raw nitrate absorbance data for 39 ponds sampled from April-July, 2013. Note, actual nitrate concentration peaked at 4.95 mg/L in one pond in July.....	82
Appendix 10. Path analyses assessing the direction and potential causes of effect of agricultural intensity on the maximum recorded abundance of anurans in ponds in the agricultural region of Eastern Ontario. Predictor variables for a given species included nitrate concentration (ni), the best measure of larval habitat quality for that species (% emergent vegetation pond cover (em), water temperature (wt), or pH), and the proportion of landscapes in each of the following: high-intensity row crop cover (hi), adult habitat (either forest (fo) or low-intensity perennial crop cover (lo)) , and wetland cover (we). The scales at which each landscape effect was strongest for each species were 250, 500, or 1000 m and were displayed with each cover type (e.g. for we500, the effects of wetlands were strongest at 500 m). Error terms (residual variance) for abundance and nitrate are denoted by 'e'	85
Appendix 11. Path analysis model fit criteria for Appendix 10: path analyses on effects of agricultural intensity on 'maximum recorded anuran abundance'. Several goodness of fit measures were included to assess the overall fit of each model, with boldness indicating a "good fit". Measures included: the X2 "badness of fit" measure (if $p < 0.05$, the model was a bad fit (Hair et al., 2006)), the comparative fit index (if $CFI \geq 0.90$, the model was a good fit (Bentler, 1990)), the Tucker-Lewis index (if $TLI > 0.95$, the model was a good fit (Bollen, 1989)), and root mean square error (if $RMSEA \leq 0.07$, the model was a good fit (Hu & Bentler, 1999))	86
Appendix 12. ANOVA output for test of significant differences of nitrate absorbance among ponds, with a random effect of sampling period	87

Introduction

Habitat loss is the primary threat to species globally (Sala et al., 2000) and to anurans in particular (Cushman, 2006; Hazell, 2003). One of the major drivers of habitat loss is agriculture (Wilcove et al., 1998; Venter et al., 2006), which is particularly detrimental to biodiversity at high intensities (e.g. Donald et al., 2006; Le Féon et al., 2010).

"Agricultural intensity" is characterized by high use of fertilizers, herbicides and insecticides, large farm sizes with large crop fields, high livestock densities, and generally high levels of mechanization (Boutin and Jobin, 1998; Donald et al., 2006; Stoate et al., 2001; Le Féon et al., 2010). Crop type can sometimes be used to classify the level of agricultural intensity, as, for example, some crops are associated with high chemical use (Boutin and Jobin, 1998). Thus, the area of a landscape containing these crops can be used as an index of the agricultural intensity of that landscape.

While it is clear that agriculturally-driven habitat loss is detrimental to anurans (e.g. Cushman, 2006; Hazell, 2003), it is unclear how varying levels of agricultural intensity might affect them. Studies on the effects of agricultural cover (e.g. Bonin et al. 1997a; Knutson et al., 2004) and chemical inputs (e.g. Hecnar, 1995; Smith et al., 2006) on anurans have found inconsistent results both between and within species. For instance, across species, all possible responses (positive, negative, or none) to both crop cover and nitrate concentrations have been observed. Similarly, one species, *Lithobates clamitans*, has shown both negative (Knutson et al., 2004) and positive (Gagné and

Fahrig, 2007) associations with agricultural cover, as well as both negative (Hecnar, 1995) and positive (Smith et al., 2006) associations with nitrate inputs.

One possible explanation for variation in anuran responses to agricultural intensity, both between and within species, is that, within a given study, agricultural intensity may be correlated, either negatively or positively, with adult habitat amount. Since habitat preferences vary by species, depending on the correlations in a given data set, this could cause apparent differences among species in their responses to agricultural intensity.

For example, if *Lithobates pipiens* abundance is determined by the availability of its adult habitat (open natural and semi-natural areas, including perennial forage crops (Mazzerole, 2001)), then, in a data set where adult habitat is negatively correlated with row crops, this will result in an apparent negative effect of agricultural intensity on this species (assuming it cannot use row crops for adult habitat). In another data set, where there happens to be a positive correlation between row crops and open natural and semi-natural areas, the apparent effect of agricultural intensity on *L. pipiens* will be positive. Similarly, in the same data set, there could be a positive correlation between row crops and open natural and semi-natural areas, but a negative correlation between row crops and forest. This could result in an apparent positive effect of agricultural intensity for *L. pipiens*, but a negative effect of agricultural intensity on *Hyla versicolor*, since *H. versicolor* uses forest for adult habitat (Johnson, 2005).

Another possible explanation for between-species variation in anuran responses to agricultural intensity is that differences in tadpole life history and sensitivity to

agrochemical toxicity may cause different responses because of effects of agricultural intensity on larval habitat. For example, species whose tadpoles rely more on algal food resources, such as *H. versicolor*, *Pseudacris crucifer*, and *Pseudacris triseriata* (Hoff et al., 1999; Quammen and Durtsche, 2003; and Whitaker, 1971; respectively), might be found in greater abundance in areas of higher agricultural intensity, so long that concentrations of agrochemicals do not reach toxic levels. This is because fertilizer inputs can increase periphyton and phytoplankton growth (Bell, 2002; Maberly et al., 2002), which can increase tadpole growth (Leibold and Wilbur, 1992; Kiffney and Richardson, 2001; Wijer et al., 2003). In contrast, for species that are sensitive to agrochemical toxicity, we might expect that chemical inputs from high-intensity agriculture could reduce larval habitat quality by decreasing survivorship and hatch rates (Bonin et al., 1997b; Relyea, 2005; Reylea et al., 2011). Agricultural contaminants can also be associated with hindlimb deformities (Ouellet et al., 1997), sexual differentiation changes (Orton et al., 2006), and disrupted thyroid activity pathways in anurans (Fort et al., 2004). Even fertilizer inputs can become toxic for some embryonic and larval anurans (Hecnar, 1995), when resulting nitrate concentrations exceed 5 mg/L (see Table 2).

Within-species variation in responses to agricultural intensity could be explained by differences among studies in: definitions or measures of agricultural intensity; spatial scales used in landscape studies; and chemical exposure dosages used in lab experiments. Some studies measure agricultural intensity using indicator values such as livestock density and chemical inputs (e.g. Le Féon et al., 2010), while others include

yield values and numbers of tractors per unit area (e.g. Donald et al., 2006). Different aspects of agricultural intensity may affect a given species in different ways. For instance, tillage and the use of machinery and insecticides may reduce the abundance of *Cydinae* burrowing bugs (Chapin and Thomas, 2003), but we do not know how increased fertilizer use or increased crop field size might affect them. Similarly, measuring landscape variables, such as row crop cover, over different spatial extents could cause within-species variation in the literature. For example, some insects show differing responses to some of the same landscape predictors depending on the scale at which the predictor is measured (e.g. Holland et al., 2004; Hirao et al., 2008; Thomson et al., 2010). Finally, different chemical exposure concentrations can have different or even contrasting effects on larval anurans, as seen with *L. clamitans*, which showed increased growth in nitrate-nitrogen concentrations of 5 mg/L (Smith et al., 2006), but reached LC50 at 144 mg/L (Hecnar, 1995).

Our study aims to address the questions: do different anuran species respond differently to agricultural intensity? If so, what could be driving these differences? We surveyed anurans in agricultural ponds, and we defined agricultural intensity as the proportion of the landscape surrounding the pond that is covered by intensively-produced row crops. We selected the ponds to represent a wide range of row crop cover in the surrounding landscapes. We also measured the proportion of the surrounding landscapes in perennial crops, forests, and wetlands, which can serve as adult habitat for some species. Finally we collected water samples from the ponds, from which we estimated nitrate concentrations.

Based on the arguments above, we tested the following predictions. In landscapes surrounding breeding ponds, if the amount of adult habitat of a given anuran is negatively correlated with row crop cover, we expected a negative effect of crop cover (agricultural intensity) on the abundance of that species in the ponds. For species whose tadpoles rely more on algal food resources, we expected positive relationships to both agricultural intensity and nitrate, as long as nitrate concentrations are below toxic levels for those species (see Table 2 for documented nitrate effects).

Methods

Overview

We selected 39 ponds in the agricultural areas within Eastern Ontario (Figure 1). In this region, row crops are mainly corn, soy, and cereal grains. Perennial grass, hay fields, and alfalfa/clover fields are also common, and the agricultural fields are interspersed with woodlands, wetlands, and small urban areas. To measure agricultural intensity, we calculated the proportion of landscape cover in row crops within 100, 250, 500, 1000, 2000, and 4000 m of each of the 39 ponds. We also calculated proportions of forest, perennial crops, and wetlands at the same scales. We measured anuran abundances, and a suite of local pond variables, in each of the 39 ponds. We used generalized linear models to determine the scale of effect of each landscape predictor (row crop cover, forest, perennial crops, and wetlands) on the abundance of each species (Elliott et al., 1999). We used correlations to determine the single best local measure of larval habitat

quality for each species. We then conducted path analyses to determine the direction and potential causes of effect of agricultural intensity on the abundance of each species. For each species, the path analysis included the amounts of row crop cover, adult habitat, and wetlands, in the landscape, and nitrate concentration and larval habitat quality, in the pond.

Site selection

We used three data sources for site selection: OMAFRA's Agricultural Resource Inventory (for urban areas, forests, and agricultural land use types (OMAFRA, 2010)), the Ontario Hydro Network (OHN) - Waterbody polygon (for ponds (OHN, 2010)), and the NRVIS/OLIW Data Management Model For Wetland Unit (for wetlands (Land Information Ontario, 2011)). We used ArcMap 10.1 to conduct all GIS analyses (ESRI, Redlands, CA, USA).

Site selection proceeded as follows. First, we used the OHN waterbody polygon to find ponds in Eastern Ontario that were 20-100 m in diameter and at least 1 km from major water sources. 1688 ponds met this criterion. We considered ponds of 20-100 m diameter because, in this size range, we could expect to find any of the anuran species in our region. Choosing ponds that are isolated from other water sources reduced the potential for population spillover effects.

We then calculated the proportion of row crop cover (predominantly corn, but also soy, cereal grains, and beans) within 500 m of each pond. We chose 500 m for this initial

step because it falls in the middle of the known scales at which landscape context affects anurans in our region (Eigenbrod et al., 2008). Since we were looking for ponds in landscapes of varying row crop cover proportions, we removed any ponds in landscapes that did not contain row crops, resulting in 302 landscapes with crop cover ranging from 0.3 - 92.5 % (mean 18.3 ± 24.4 SD) within 500 m.

From these we removed any ponds in landscapes containing former quarries, extraction pits, livestock pastures, or large urban areas, which may produce chemical inputs other than those associated with row crops. After visual examination of satellite imagery, we also removed ponds that had highly degraded edges (with little vegetation), indicating use by livestock. Since we were interested in agriculturally situated ponds, we also removed any that were bordered by more than 50% trees or forest. This reduced our potential set of ponds to 77. This number was further reduced to 63, after ponds within 2 km of each other were excluded, to prevent pseudoreplication.

Finally, while obtaining permissions from landowners to sample their ponds, we asked them whether the ponds were artificial and whether they were subject to management activities that might influence anurans, such as use for watering holes, fish stocking, or irrigation. These ponds were excluded, giving us a set of 41 candidate ponds. We began the field season with these 41 sites, but ended with 39, as two ponds were drained during the summer.

Anuran call surveys

We took 10-minute chorus surveys at each pond 4 times. We used the following abundance classes: 0 (no calls), 1 (distinct calls of separate individuals), 2 (some calls overlap but most individuals can still be identified), and 3 (mostly overlapping calls and continuous calling) (modified from Bishop et al., 1997). We conducted surveys in a randomized order (as per Eigenbrod et al., 2008,) on nights from April 15th (when the first *P. crucifer* were heard) until July 29th, 2013, allowing for coverage of all species' breeding seasons. Two to four ponds were sampled per night. If a given pond was surveyed first on one night, it would be surveyed last in the night during the next round of surveys, to reduce the influence of survey order. We summed the abundance ranks across the four survey dates for each species at each pond (Pope et al., 2000).

Local Pond Variables

During each survey, we measured a number of environmental and local pond variables. Weather conditions (cloud cover, precipitation, and wind speed) were noted using relative ranks. We recorded the following local water parameters, two metres from the shore, prior to each survey: water temperature, electrical conductivity (an indicator of salinity), and pH; each measured with a Hanna Instrument handheld tester (HI98129) held at the pond surface; pond depth, measured with weighted measuring tape; and water clarity, measured with a Secchi disk tube. We visually estimated the percent of pond surface covered by open water or floating, emerging, or submerged vegetation, as well as the percent of pond circumference covered by overhanging vegetation (which we considered to be any plant taller than two metres). We also later measured pond

area using the OHN waterbody polygon (OHN, 2010). During each survey, we took water samples to the lab and analyzed them for nitrate concentration, using the cadmium reduction method with a spectrophotometer and NitraVer® 5 Nitrate Reagent Powder Pillows (as per APHA, 1998).

Landscape Variables

Landscape variables (high- and low-intensity agricultural cover, wetlands and forest) were the proportion of each cover type covering the landscape surrounding the pond at each scale (see below). High-intensity agricultural cover was defined as the proportion of landscape cover in row crops (corn, soy, cereal grains, and beans), while low-intensity agricultural cover was the proportion in perennial crops (hay and alfalfa fields).

Although field work was conducted in 2013, the polygons used for row crops, perennial crops, forests, and ponds were created in 2010, and the polygon used for wetlands was created in 2011. These time gaps could have been responsible for errors in landscape representation.

Data Analyses

Scales of effect

We created six nested landscapes (with 100, 250, 500, 1000, 2000, and 4000 m radii) around each pond to examine the scale at which the effect of each landscape predictor on the abundance of each species was strongest (its scale of effect, (Weins, 1989)). For

each species, these scales were identified for: percent row crop cover, percent adult habitat cover—either forest or perennial crops, depending on each species' documented adult habitat (see Table 3), and wetlands, since ponds with more surrounding wetland may receive more anuran immigrants.

To determine the scale of effect of each landscape predictor on the abundance of each species, we used generalized linear models, with negative binomial distributions (to account for over-dispersed abundance data) and log link functions. The scale with the highest absolute β -coefficient value for the effect of each landscape predictor on the abundance of each species was considered to be the scale of effect for that predictor on that species.

Larval habitat quality

We examined correlations between the abundance of each species and local predictors (pH, nitrogen concentration, water temperature, conductivity (a measure of salinity), depth, pond area, water clarity, and percent of: overhanging vegetation, open water, submergent vegetation, emergent vegetation, and floating vegetation). The local predictor with the highest absolute Pearson correlation value was considered the single best local measure of larval habitat quality for each species. We only identified a single best measure of larval habitat quality for a given species to avoid the risk of over-specifying the final models.

Path Analyses

Path analyses constructed path models for each species, to determine the direction and potential causes of effect of agricultural intensity, at its scale of strongest effect, on the abundance of each species. Predictor variables for a given species included nitrate concentration, the best measure of larval habitat quality for that species, and the proportion of the landscape in each of the following: row crop cover, adult habitat for that species, and wetland cover (each at its scale of strongest effect). We used path analysis rather than multiple regression because we expected an indirect effect of agricultural intensity through its effect on nitrate concentration. We used SPSS version 22.0.0 for initial statistical analyses and SPSS Amos Graphics 22.0.0 for path analyses (IBM, Meadville, PA, USA).

Results

We found eight out of the ten anuran species that occur in our region (Figure 2; *Lithobates palustris* and *Lithobates septentrionalis* were not found). Ponds had on average 3.95 species, with each having at least one species and none having more than six.

The range of row crop cover in the landscapes was 0.3 - 88.8 % (mean 30.6 ± 25.7 SD) within 500 m of the ponds and 3.6 - 85.2 % (mean 24.6 ± 19.4 SD) within 1000 m (see Appendix 2 for all cover types at all scales). Landscape predictor correlations are in Table 4. Only 250, 500, and 1000 m scales were considered because of high landscape predictor correlations between crop cover and habitat at other scales (Appendix 6),

which would have reduced result interpretability. Row crop cover was negatively correlated with forest, wetland, and perennial crop cover, at all three scales. Forest cover and perennial crop cover were negatively correlated with each other, but positively correlated with wetlands, at all three scales, with the exception of 1000 m, where perennial cover was negatively correlated with wetlands. The range in values of nitrate concentrations across ponds was 0.43 - 2.99 mg/L (mean 1.14 ± 0.59 SD).

Correlations among the local habitat predictors are in Table 5. Strong negative correlations were found between percent open water and percent of both submerged and emergent vegetation cover. Moderate negative correlations were found between percent open water and floating vegetation cover, and between pond depth and water clarity. Moderate positive correlations were found between: percent emergent and submerged vegetation cover, pond area and percent open water, and percent open water and pond pH.

In the path analyses (Figure 3), we included only the single strongest local habitat predictor for each species (Table 6) because the number of estimable paths was limited by our sample size (39); to produce reliable results, sample size should generally be at least five times the number of paths estimated (Petraitis et al., 1996). The local variables included in the path analyses were: water temperature for *Lithobates clamitans*, *Lithobates sylvaticus*, *Pseudacris crucifer*, and *Pseudacris triseriata*; pH for *Anaxyrus americanus*; and % emergent vegetation for *Hyla versicolor*, *Lithobates catesbeianus*, and *Lithobates pipiens*.

Species responses to agricultural intensity

Overall, our results indicate that different species do respond differently to agricultural intensification. Each species' path analysis included row crop cover and nitrate concentration, plus the amount of wetland cover in the surrounding landscape, the amount of adult habitat for that species (Table 3) in the surrounding landscape, and the most important local pond predictor for that species (Table 6). Each of the three landscape predictors was included at its strongest scales of effect for that species (250 m, 500 m, or 1000 m; see Appendix 1 for plots used to determine scales of effects.) Only 250, 500, and 1000 m scales were considered because landscape predictor correlations at other scales (100, 2000, and 4000 m) were high enough to make the effects of each indistinguishable. The path analyses for the 8 anuran species revealed both negative and positive responses to both row crop cover and nitrate concentration (see Figure 3 and Table 7.) For example, *A. americanus* was positively associated with both row crop cover and nitrate concentration, *H. versicolor* was negatively associated with both row crop cover and nitrate concentration, and *L. pipiens* and *L. sylvaticus* showed opposite and opposing responses to row crop cover and nitrate concentration.

Discussion

Our results confirmed that different anurans respond differently to agricultural intensity, as we observed all possible combinations of responses to row crop cover and nitrate concentration. These findings are generally consistent with the literature, which

has found extremely variable responses across species (Tables 1 and 2). The fact that we found these differences among species within a single study, with a consistent definition of agricultural intensity and empirically identified scales of effect, indicates that the differences among species are real, and not just a result of differences in definitions and scales among studies.

What drives the differences between anurans species in their responses to agricultural intensity?

Overall, our results suggest that differences among species are likely related to correlations between agricultural intensity and adult habitat amount (negative or positive) and to the effects of agricultural intensity on larval habitat quality and food availability. Overall, the negative effects of row crop cover are weaker than its positive effects.

Anaxyrus americanus showed positive associations with both row crop cover and nitrate. *A. americanus* was more positively associated with row crops than any of the other species in our study. It is likely that agricultural cover (both perennial and row crop) can function as adult habitat for this species. The known habitat for *A. americanus* includes semi-natural gardens and grasslands (Klemens, 1993), and our results suggest it may also include row crops. The positive effect of nitrate concentration on *A. americanus* may have been due to the positive correlation between row crop cover and nitrate concentration ($r = 0.31$ at 500m), although the path analysis is meant to account for such correlations to a certain degree (Bentler and Chou, 1987).

Lithobates pipiens also had a positive association with row crop cover, likely also because it can use crop fields as adult habitat. The known habitat for *L. pipiens* is open natural and semi-natural habitats, such as perennial crops (Merrell, 1977; Mazzerole, 2001; Guerry and Hunter, 2002), but our results suggested a stronger relationship of this species to row crops than to perennial crops, at least in our region. We did not expect *L. pipiens* to have a negative association with perennial crop cover based on its known habitat associations (see Table 3). Unlike *A. americanus*, *L. pipiens* had a negative association with nitrate concentration, perhaps due to decreased larval habitat quality. We suggest this because *L. pipiens* is sensitive to nitrate toxicity (Hecnar, 1995). The weaker positive association of *L. pipiens* with row crop cover, when compared to *A. americanus*, could be explained by the negative effect of nitrate concentration on this species, combined with the positive correlations between row crop cover and nitrate.

A third species, *Lithobates catesbeianus*, also had a positive association with row crop cover. However, this was likely not due to an association with adult habitat, as this species is strongly aquatic (Conant and Collins, 1975). We speculate that the apparent positive effect of row crop cover on this species was due to its negative correlation with emergent vegetation cover in ponds ($r = -0.25$ at 500 m), and the negative correlation between emergent vegetation cover and *L. catesbeianus* abundance ($r = -0.45$).

However, we note that, overall, the path analysis for this species is confusing, as it shows a negative effect of wetland cover, which is unexpected based on known habitat associations for this species (see Table 3).

Three species (*Hyla versicolor*, *Lithobates sylvaticus*, and *Pseudacris triseriata*) were negatively associated with row crop cover, likely because of the negative correlations between high-intensity crop cover and their adult habitat (forest). *H. versicolor* also had negative associations with nitrate concentration, but has been previously been shown not to be sensitive to nitrate toxicity (Boone and Bridges-Britton, 2006). This negative effect may have been caused by the correlation between high-intensity crop over and nitrate. In contrast, *L. sylvaticus* showed a positive association with nitrate. This species is not susceptible to nitrate toxicity in concentrations lower than 50 mg/L ammonium nitrate (see Table 2), so we hypothesize that this positive association was due to increased algal abundance (for larval food).

The two remaining species—*Lithobates clamitans* and *Pseudacris crucifer*—also had positive associations with nitrate. We suggest that these responses were also due to increased larval food. *L. clamitans* is not susceptible to nitrate toxicity in concentrations lower than 44 mg/L nitrate-nitrogen (see Table 2), while the nitrate susceptibility of *P. crucifer* has not been tested.

Overall, our results support our prediction of variable responses across anurans to agricultural intensity. Row crop cover is negatively related to adult habitat for some species and positively for others. Nitrate can improve larval habitat for some species but reduces larval habitat quality for others.

Study limitations

We were not able to assess pesticide levels in our ponds, and we considered nitrate to be an indicator of overall chemical use. Ponds with higher pesticide inputs typically also have higher fertilizer inputs (Geiger et al., 2010) and are more associated with row crop fields than perennial fields (Boutin and Jobin, 1998). We do not believe pesticides were responsible for the unexpected negative associations between *L. pipiens* and perennial crop cover, and *L. catesbeianus* and wetland cover, since we don't suspect that pesticide use is associated with these cover types. However, we cannot rule out the idea that the effects of row crop cover and nitrate we observed were influenced by pesticide use.

The abundance surveys we used were taken at night throughout the season and may have been influenced by both weather variability and the breeding phenology of each species. Since our use of summed-abundance ranks may have overestimated the abundance of anurans that called more continuously throughout the seasons, we reran path analyses using maximum-abundances, which should not be as influenced by seasonality as summed-abundances (see Appendices 10 and 11). The direction of effects of agricultural intensity on the abundance of each species did not differ from our original path analyses, when using maximum-abundance ranks, and any differences in effect strength were small.

Our ponds had nitrate levels ranging between 0.43 and 4.94 mg/L, while watersheds throughout North America can have levels ranging anywhere from < 1 to 100 mg/L (Rouse et al., 1999). The effects of nitrate on anurans can vary depending on concentration, as seen in laboratory studies (Table 2). Since the range of nitrate values

observed in our ponds was small, we confirmed that the differences in nitrate values among ponds were significant (see Appendix 12).

Our study was limited to the agricultural region of Eastern Ontario and the particular agricultural practices of this region. The effects of agricultural intensity may differ in other regions with different anurans, regulations, and/or crops. For instance, in areas that ineffectively regulate pesticide use (see Ecobichon, 2001; Schreinemachers and Tipraqsa, 2012), we may expect to find stronger negative effects of agricultural intensity than in areas such as Prince Edward Island, where buffer zone regulation significantly reduces wetland contamination (Dunn et al., 2011).

Implications

Our results call into question several extrapolations that are sometimes made about the effects of agricultural intensity on anurans. Since we found marked differences among anuran species in their responses to both nitrate and row crop cover, studies on single anuran species should not be extrapolated to other anurans. Our results also suggest that extrapolating from laboratory nitrate effects to nitrate effects in the field is problematic, particularly when nitrate concentrations in the field are much lower than those used in lab tests. Many of the species included in our study responded positively to nitrate, but negatively in previous studies using higher concentrations (see Table 2). Lastly, our results suggest that making extrapolations from either row crop cover effects or nitrate effects to agricultural intensity effects is not justified, since these factors had opposite effects on some species.

Overall, our results suggest that agricultural intensity itself is not strongly affecting anurans in our region. The negative effects of row crop cover are generally weaker than its positive effects. Fertilizer applications, at least at the levels present in our area, do not appear to be detrimental to anuran abundance. On the other hand, our results confirm that habitat loss due to agriculture has a significant effect on anurans, particularly for species that rely on forests for adult habitat, such as *P. triseriata*, *H. versicolor*, and *L. sylvaticus*.

Agricultural intensity

Habitat loss due to agriculture is undeniably a major threat to species globally (Wilcove et al., 1998; Sala et al., 2000; Venter et al., 2006). However, our results suggest that, within some agricultural landscapes, some species (e.g. *A. americanus*) can persist and breed in abundance, indicating that agriculture, in this case, does not necessarily constitute part of 'habitat loss'. Other species, particularly those associated with forest or sensitive to one particular aspect of intensive agriculture (e.g. agrochemical use), are likely at greater risk from agriculture.

The term 'agricultural intensity' is used inconsistently in the ecology literature, referring to anything from quantities of insecticide sprayed to sizes of crop fields. In light of this, we suggest that the term be more narrowly defined to promote consistent, ecologically relevant, use in the literature. Habitat effects should be described as habitat effects, whereas effects of 'agricultural intensity' should refer only to the effects of increased chemical usage (i.e. for a particular crop type), independent of habitat amount. We

suspect that, in general, for species persisting in agricultural landscapes, the effects of habitat amount are more important than the effects of agricultural intensity, independent of habitat amount.

Tables

Table 1. Landscape studies examining the effects of proportion of agricultural land cover on anurans. Response variables included anuran abundance, species richness, and reproductive success.

Species or Species Set	Response Variable	Measure of Agricultural Intensity; % landscape in:	Direction of Effect and Significance	Reference(s)
<i>Acris crepitans</i> , <i>Anaxyrus americanus</i> , <i>A. cognatus</i> , <i>A. woodhousii</i> , <i>Hyla</i> <i>chrysoscelis</i> , <i>H. versicolor</i> , <i>Lithobates</i> <i>catesbeianus</i> , <i>L. clamitans</i> , <i>L. palustris</i> , <i>L.</i> <i>pipiens</i> , <i>L. septentrionalis</i> , <i>L. sylvaticus</i> , <i>Pseudacris crucifer</i> , <i>P. triseriata</i>	species richness and maximum abundance index	grazed land and row crop	positive*	Knutson et al. (1999)

<i>Ambystoma tigrinum mavortium</i> ^a ,	mean daily	pasture	positive*	Gray et al.
<i>Anaxyrus cognatus</i> , <i>A. woodhousii</i> , <i>L. blairi</i> , <i>P. clarkii</i> , <i>S. bombifrons</i> , <i>S. multiplicata</i>	amphibian			(2004)
<i>A. americanus</i> , <i>H. versicolor</i> , <i>L. clamitans</i> , <i>L. palustris</i> , <i>L. pipiens</i> , <i>L. sylvaticus</i> , <i>P. triseriata</i> , <i>P. crucifer</i>	species richness	non-grazed pasture and row crop	no significant effect	Knutson et al. (2004)
<i>A. americanus</i> , <i>H. versicolor</i> , <i>L. clamitans</i> , <i>L. pipiens</i> , <i>L. sylvaticus</i> , <i>P. crucifer</i>	species richness	monoculture	negative, NS	Bonin et al. (1997a)
<i>A. americanus</i> , <i>H. versicolor</i> , <i>L. clamitans</i> , <i>L. pipiens</i> , <i>L. sylvaticus</i> , <i>P. crucifer</i>	species richness	> 70% non-forested land cover	no significant effect	Gagné and Fahrig (2007)

<i>B. quercicus, G. carolinensis, H. cinerea,</i>	tadpole species	pasture	negative, NS	Babbitt et al.
<i>H. femoralis, H. gratiosa, H. squirella, P.</i>	richness			(2009)
<i>ocularis, R. grylio, R. sphenoccephalia</i>				
<i>A. americanus</i>	abundance	> 70% non-forested land cover	positive, NS	Gagné and Fahrig (2007)
<i>A. americanus</i>	reproductive success index	non-grazed pasture and row crop	positive, NS	Knutson et al. (2004)
<i>H. versicolor</i>	abundance	> 70% non-forested land cover	negative, NS	Gagné and Fahrig (2007)
<i>H. versicolor</i>	reproductive success index	non-grazed pasture and row crop	positive*	Knutson et al. (2004)
<i>L. clamitans</i>	reproductive success	non-grazed pasture and row	negative, NS	Knutson et al.

	index	crop		(2004)
<i>L. clamitans</i>	abundance	> 70% non-forested land	positive, NS	Gagné and
		cover		Fahrig (2007)
<i>L. pipiens</i>	abundance	> 70% non-forested land	positive, NS	Gagné and
		cover		Fahrig (2007)
<i>L. pipiens</i> & <i>L. palustris</i>	reproductive success	non-grazed pasture and row	negative*	Knutson et al.
	index	crop		(2004)
<i>L. sylvaticus</i>	abundance	> 70% non-forested land	negative*	Gagné and
		cover		Fahrig (2007)
<i>P. crucifer</i>	abundance	> 70% non-forested land	negative*	Gagné and
		cover		Fahrig (2007)
<i>P. crucifer</i>	reproductive success	non-grazed pasture and row	positive*	Knutson et al.

	index	crop		(2004)
<i>P. triseriata</i>	reproductive success	non-grazed pasture and row	no significant	Knutson et al.
	index	crop	effect	(2004)
<i>Spea multiplicata</i>	abundance	pasture	positive*	Gray et al.
				(2004)
<i>Spea bombifrons</i>	abundance	pasture	positive*	Gray et al.
				(2004)

(^a) a salamander, (*) denotes significance at $p < 0.05$, (NS) denotes not statistically significant

Table 2. Experimental studies on the effects of nitrate on anuran survivorship and/or growth. Only studies that conducted quantitative analyses were included. Response variables included tadpole relative growth rate, survivorship, or change in mass after a given amount of time, depending on the study. All forms of nitrate were converted to comparable nitrate concentrations (as per CCME, 2003).

Species	Treatment or Concentration Range	Comparable Nitrate Concentration (mg NO ₃ --L ⁻¹ .)	Response Variable	Direction of Effect and Significance	Reference(s)
<i>Ascaphus truei</i>	38-170 µg/L dissolved nitrate- nitrogen	0.17-0.75	tadpole relative growth rate	positive*	Kifney and Richardson (2001)
<i>Anaxyrus americanus</i> (Ojibway population)	53–89 mg/L ammonium nitrate	41.34–69.42	tadpole survivorship in 96-h LC50 test	negative* (LC50 at 60 mg/L)	Hecnar (1995)
<i>Anaxyrus americanus</i>	111–222 mg/L	86.58–173.16	tadpole survivorship	negative* (LC50 at	Hecnar

(Harrow population)	ammonium nitrate		in 96-h LC50 test	174 mg/L)	(1995)
<i>Anaxyrus americanus</i>	12.9 mg/L	10.00	tadpole survival to	no significant effect	Smith and
	ammonium nitrate		metamorphosis		Dibble (2012)
<i>Anaxyrus americanus</i>	12.9 mg/L	10.00	tadpole body length	negative* (body	Smith and
	ammonium nitrate		and mass after 36	length) and positive*	Dibble (2012)
			days	(body mass)	
<i>Bufo bufo</i> (reared with	20-100 mg/L	15.6–78	tadpole survival to	negative*	de Wijer et
<i>R. temporaria</i>)	ammonium nitrate		metamorphosis		al. (2003)
<i>Bufo bufo</i> (reared with	0-120 mg/L	0–93.6	tadpole survival to	no significant effect	de Wijer et
<i>R. temporaria</i>)	ammonium nitrate		metamorphosis		al. (2003)
	with substrate				
<i>Fejervarya limnocharis</i>	0.44 - 22 mg/L	0.3212–16.06	tadpole survivorship	negative* (LC50 at	Krishnamurth

	sodium nitrate		in 96-h LC50 test	33.7 mg/L)	y et al. (2008)
<i>Hyla versicolor</i>	10 mg/L ammonium nitrate	7.80	tadpole survival to metamorphosis	no significant effect	Boone and Bridges- Britton (2006)
<i>Lithobates catesbeianus</i>	5 mg/L nitrate- nitrogen	22.15–22.15	tadpole survival to metamorphosis	negative*	Smith et al. (2006)
<i>Lithobates catesbeianus</i>	5 mg/L nitrate- nitrogen	22.15–22.15	tadpole mass after 42 days	no significant effect	Smith et al. (2006)
<i>Lithobates clamitans</i>	10 mg/L nitrate- nitrogen	44.3–44.3	tadpole survivorship after 100 days	no significant effect	Hecnar (1995)
<i>Lithobates clamitans</i>	10 mg/L nitrate-	44.3–44.3	mean tadpole mass	no significant effect	Hecnar

	nitrogen		after 96 hours		(1995)
<i>Lithobates clamitans</i>	44-222 mg/L nitrate-nitrogen	194.92–983.46	tadpole survivorship in 96-h LC50 test	negative* (LC50 at 144 mg/L)	Hecnar (1995)
<i>Lithobates clamitans</i>	5 mg/L nitrate-nitrogen	22.15–22.15	tadpole survival to metamorphosis	no significant effect	Smith et al. (2006)
<i>Lithobates clamitans</i>	5 mg/L nitrate-nitrogen	22.15–22.15	tadpole mass after 42 days	positive*	Smith et al. (2006)
<i>Lithobates pipiens</i>	10 mg/L nitrate-nitrogen	44.3–44.3	tadpole survivorship after 100 days	negative*	Hecnar (1995)
<i>Lithobates pipiens</i>	10 mg/L nitrate-nitrogen	44.3–44.3	mean tadpole mass after 96 hours	no significant effect	Hecnar (1995)
<i>Lithobates pipiens</i>	44–155 mg/L	194.92–686.65	tadpole survivorship	negative* (LC50 at	Hecnar

	nitrate-nitrogen		in 96-h LC50 test	100 mg/L)	(1995)
<i>Lithobates pipiens</i>	10 mg/L sodium nitrate	7.3–7.3	tadpole survival to metamorphosis	no significant effect	Orton et al. (2006)
<i>Lithobates pipiens</i>	10 mg/L sodium nitrate	7.3–7.3	tadpole mass at metamorphosis	no significant effect	Orton et al. (2006)
<i>Lithobates sphenoccephalus utricularia</i>	0-65 mg/L ammonium nitrate	0–50.7	total tadpole biomass	positive*	Leibold and Wilbur (1992)
<i>Lithobates sylvaticus</i>	50 - 100 mg/L ammonium nitrate	39–78	tadpole survivorship after 7 days	negative*	Burgett et al. (2007)
<i>Lithobates sylvaticus</i>	5.5–89 mg/L sodium nitrate	4.015–64.97	tadpole survivorship after 96 hours	no significant effect	Smith et al. (2007)

<i>Litoria aurea</i>	10 and 15 mg/L ammonium nitrate	7.8–11.7	tadpole survival to metamorphosis	negative*	Hamer et al. (2004)
<i>Litoria aurea</i>	22.7 mg/L nitrate-nitrogen	100.56	tadpole survivorship after 13 days	negative*	Baker and Waights (1993)
<i>Nyctibatrachus major</i>	0.44 - 22 mg/L sodium nitrate	0.32-16.06	tadpole survivorship in 96-h LC50 test	negative* (LC50 at 9 mg/L)	Krishnamurthy et al. (2008)
<i>Pseudacris triseriata</i>	10 mg/L nitrate-nitrogen	44.3–97.46	tadpole survivorship after 100 days	negative*	Hecnar (1995)
<i>Pseudacris triseriata</i>	10 mg/L nitrate-nitrogen	44.30	mean tadpole mass after 96 hours	no significant effect	Hecnar (1995)
<i>Pseudacris triseriata</i>	111–200 mg/L	491.73–886	tadpole survivorship	negative* (LC50 at 75	Hecnar

	nitrate-nitrogen		in 96-h LC50 test	mg/L)	(1995)
<i>Rana temporaria</i>	43–128 mg/L nitrate	43–128	embryo survivorship	no significant effect	de Wijer et al. (2003)
	from calcium nitrate				
<i>Rana temporaria</i>	20-100 mg/L	15.6–78	tadpole survival to	negative*	de Wijer et al. (2003)
(reared with <i>B. bufo</i>)	ammonium nitrate		metamorphosis		
<i>Rana temporaria</i>	0-120 mg/L	0–93.6	tadpole survival to	no significant effect	de Wijer et al. (2003)
(reared with <i>B. bufo</i>)	ammonium nitrate		metamorphosis		
	with substrate				

(*) denotes significance at $p < 0.05$, (NS) denotes not statistically significant.

Table 3. Life history characteristics of anurans in eastern Ontario.

Species	Larval period	Reference(s)	Larval Diet	Reference(s)	Adult Habitat	Reference(s)
<i>A. americanus</i>	50–60 days	Wright & Wright, 1949	omnivorous (plant material, periphyton, detritus, and dead fish or tadpoles)	Ahlgren & Bowen, 1991, Quammen & Durtsche, 2003	Open natural and semi-natural areas/generalist: grasslands, gardens, fields, lawns, barnyards, and forests.	Klemens, 1993
<i>H. versicolor</i>	45-65 days	Wright, 1932	primarily algae and periphyton	Hoff et al., 1999	Forest: trees and vegetated fences, forested areas	Conant & Collins, 1998, Johnson, 2005
<i>L.</i>	a few	Bury &	algae, aquatic plant	Bury &	Wetlands and Forest, strongly	Storer,

<i>catesbeianus</i>	months to 3 years	Whelan, 1984	material, and some invertebrates	Whelan, 1984	aquatic: herbaceous wetlands, forested wetlands, vegetated shoals, sluggish backwaters and oxbows, farm ponds, reservoirs, marshes, and still waters, lakes, rivers, creeks, and streams	1922; Hammerson, 1999, Conant & Collins 1975
<i>L. clamitans</i>	about 3 months to 2 years	Collins, 1993; Pauley & Lannoo., 2005	primarily on algae, but also crustaceans and fungi	Werner & McPeck, 1994	Wetlands and Open natural and semi-natural areas, semi-aquatic: shorelines of lakes and of ponds, bogs, fens, marshes, swamps, and streams.	Collins, 1993
<i>L. pipiens</i>	about 50-70 days	Lannoo, 1996	algae, plant material, detritus, invertebrates, and	McAllister et al., 1999	Open natural and semi-natural areas: typically grassy areas, meadows, or fields but can include	Merrell, 1977; Mazzerole,

			other vertebrates (including other tadpoles)		other sites such as peat bogs and perennial forage crops	2001; Guerry & Hunter, 2002
<i>L. sylvaticus</i>	65-130 days	Redmer, 2002	detritus, plant material, periphyton, may also cannibalize conspecifics and prey upon other aquatic animals	Petranka & Thomas, 1995, Quammen & Durtsche, 2003	Wetlands and Forest: willow thickets, wet meadows, bogs, and temperate forests (both coniferous and deciduous)	Conant & Collins, 1998, Redmer, 2002
<i>P. crucifer</i>	about 3 months	Wright & Wright, 1949	primarily algae and periphyton	Quammen & Durtsche, 2003	Wetlands and Forest: lowland marshes, wetlands, sphagnum bogs and cattail Wetlands and Forest:	Wright & Wright, 1949

					wetlands, ponds, pools, and ditches	
					in and near woods	
<i>P. triseriata</i>	40-90 days	Whiting, 2004	primarily algae	Whitaker, 1971	Wetlands and Forest: damp meadows, marshes, forest edges, bottomland swamps, and temporary ponds.	Gibbs et al., 2007

Table 4. Pearson correlations for potential landscape predictors (measured as percent cover) in 250, 500 and 1000 m - radius landscapes. Significant correlations $p < 0.05$ are denoted by * and $p < 0.01$ by **. Low-intensity agricultural cover consisted of perennial crops, while high-intensity agricultural cover consisted of row crops. The other two predictors were forest cover and wetland cover in the landscapes.

Cover Type	High-Intensity Agricultural	Low-Intensity Agricultural	Wetland
250 m - Radius Landscapes			
Low-Intensity Agricultural	-.536**		
Wetland	-0.248	0.289	
Forest	-0.173	-0.122	0.169
500 m - Radius Landscapes			
Low-Intensity Agricultural	-.584**		
Wetland	-0.215	0.136	
Forest	-0.191	-0.168	0.304
1000 m - Radius Landscapes			
Low-Intensity Agricultural	-.378*		
Wetland	-0.14	-0.12	
Forest	-0.292	-0.306	.395*

Table 5. Pearson correlation values for correlations between potential local habitat predictors of anuran abundance in 39 sample ponds in the agricultural region of Eastern Ontario. Boldness indicates absolute Pearson correlation values > 0.3. Significant correlations of $p < 0.05$ are denoted by *, $p < 0.01$ by **.

Pond Variables	Water Temp.	pH	Elect. Cond.	Depth	Water Clarity	Overhanging Vegetation	Pond Area	% Open Wat. Cover	% Subm. Veg. Cover	% Emerg. Veg. Cover
pH	.117									
Conductivity	.208	-.293								
Depth	.003	.150	-.207							
Water Clarity	-.080	-.162	.050	-.387*						
Overhanging Vegetation	-.056	-.150	-.201	-.231	.040					
Pond Area	.093	-.123	.083	-.072	.055	-.096				
% Open Water Cover	.052	.358*	-.165	.294	-.158	-.116	.302			
% Subm. Veg. Cover	-.151	-.386*	.217	-.326*	.153	.041	-.266	-.649**		
% Emer. Veg. Cover	.007	-.285	.148	-.365*	.048	.299	-.212	-.807**	.517**	

% Float. Veg. Cover	.123	-.128	.144	-.003	.107	-.038	-.023	-.338*	-.029	-.011
---------------------	------	-------	------	-------	------	-------	-------	---------------	-------	-------

Table 6. Pearson correlations between anuran abundance and local pond predictors in 39 sample ponds in the agricultural region of Eastern Ontario. Boldness indicates the highest absolute Pearson correlation value for each species. Significant correlations of $p < 0.05$ are denoted by (*), $p < 0.01$ by (**).

Pond Variables	<i>Anaxyrus</i>	<i>Hyla</i>	<i>Lithobates</i>	<i>Lithobates</i>	<i>Lithobates</i>	<i>Lithobates</i>	<i>Pseudacris</i>	<i>Pseudacris</i>
	<i>americanus</i>	<i>versicolor</i>	<i>catesbeianus</i>	<i>clamitans</i>	<i>pipiens</i>	<i>sylvaticus</i>	<i>crucifer</i>	<i>triseriata</i>
Water Temperature	.324*	.036	-.115	.447**	-.023	-.552**	-.440**	-.348*
pH	.407*	.056	.267	-.048	-.007	-.327*	-.210	.140
Conductivity	-.003	-.109	.076	.057	.082	.070	-.158	-.330*
Depth	.063	.024	.123	-.065	-.121	-.040	-.261	-.057
Water Clarity	-.132	.039	.020	.064	.242	.093	.314	.016
Pond Area	.393*	-.044	.098	.271	-.175	.224	.082	-.034
Overhanging Veg.	.008	-.002	-.276	-.105	-.022	.226	-.038	-.188
% Open Water Cover	.186	-.236	.379*	.109	-.335*	-.125	-.309	-.050
% Subm. Veg. Cover	-.262	-.054	-.372*	.008	.316*	.210	.363*	.009
% Emerg. Veg. Cover	-.047	.264	-.449**	-.051	.338*	.172	.342*	.040

% Float. Veg. Cover	.024	.211	-.064	.073	-.092	.064	.063	.029
---------------------	------	------	-------	------	-------	------	------	------

Table 7. Path analysis model fit criteria and path coefficients. Several goodness of fit measures were included to assess the overall fit of each model, with boldness indicating a "good fit".

Measures included: the χ^2 "badness of fit" measure (if $p < 0.05$, the model was a bad fit (Hair et al., 2006)), the comparative fit index (if CFI ≥ 0.90 , the model was a good fit (Bentler, 1990)), the Tucker-Lewis index (if TLI > 0.95 , the model was a good fit (Bollen, 1989)), and root mean square error (if RMSEA ≤ 0.07 , the model was a good fit (Hu & Bentler, 1999)).

Species	High Intensity Row Crop Cover Path Coefficient	Nitrate Conc. Path Coefficient	Model χ^2 , df, p	Model Fit Indices		
				CFI	TLI	RMSEA
<i>A. americanus</i>	0.39	0.24	6.33, 6, 0.39	0.96	0.86	0.038
<i>H. versicolor</i>	-0.14	-0.15	2.64, 6, 0.85	-	-5.08	0
<i>L. catesbeianus</i>	0.24	0.06	5.65, 6, 0.46	1.0	1.08	0
<i>L. clamitans</i>	0.01	0.20	3.7, 6, 0.62	-	-3.87	0
<i>L. pipiens</i>	0.14	-0.12	3.54, 6, 0.68	1.0	10.44	0
<i>L. sylvaticus</i>	-0.15	0.25	11.15, 6, 0.08	0.7	-0.05	0.15
<i>P. crucifer</i>	-0.02	0.13	5.83, 6, 0.44	1.0	1.109	0
<i>P. triseriata</i>	-0.12	-0.08	5.82, 6, 0.44	1.0	1.195	0

Figures

Figure 1. Distribution of ponds sampled for anurans with call surveys, in the agricultural region of Eastern Ontario (n = 39). Each pond is represented by a circle with shading indicating percent high-intensity agricultural land cover (row crops) within 500 m of the pond. Other areas of high-intensity agricultural land cover on the map are represented by green, while areas of low intensity agricultural land cover (perennial crops) are represented by yellow.

Figure 2. The proportion of 39 study ponds in the agricultural region of Eastern Ontario at which anurans were found during call surveys (4 surveys per pond) on nights from April 15th until July 29th, 2013.

Figure 3. Path analyses assessing the direction and potential causes of effect of agricultural intensity on the abundance of anurans in the agricultural region of Eastern Ontario. Predictor variables for a given species included nitrate concentration (ni), the best measure of larval habitat quality for that species (% emergent vegetation pond cover (em), water temperature (wt), or pH), and the proportion of landscapes in each of the following: high-intensity row crop cover (hi), adult habitat (either forest (fo) or low-intensity perennial crop cover (lo)), and wetland cover (we). The scales at which each landscape effect was strongest for each species were 250, 500, or 1000 m and were displayed with each cover type (e.g. for we500, the effects of wetlands were strongest at 500 m). Error terms (residual variance) for abundance and nitrate are denoted by 'e'. 45

References

- Ahlgren, M.O. and S.H. Bowen. (1991). Growth and survival of tadpoles (*Bufo americanus*) fed amorphous detritus derived from natural waters. *Hydrobiologia* 218:49–51.
- American Public Health Association (APHA). (1998). Standard methods for the examination of water and wastewater, American Water Works Association, and Water Environment Federation, United Book Press, Washington, D.C.
- Babbitt, K. J., Baber, M.J., and L. A. Brandt. (2006). The effect of woodland proximity and wetland characteristics on larval anuran assemblages in an agricultural landscape. *Canadian Journal of Zoology* 84:510–19.
- Babbitt, K.J., Baber, M.J., Childers, D.L. and D. Hocking. (2009). Influence of agricultural upland habitat type on larval anuran assemblages in seasonally inundated wetlands. *Wetlands* 29.1:294-301.
- Baker, J. M. R., and V. Waights. (1994). The effects of nitrate on tadpoles of the tree frog (*Litoria caerulea*). *Herpetology Journal* 4:106-108.
- Bell, T. (2002). The ecological consequences of unpalatable prey: phytoplankton response to nutrient and predator additions. *Oikos* 99: 59 –68.
- Bentler, P. M. and C.P. Chou. (1987). Practical issues in structural modeling. *Sociological Methods & Research*, 16.1:78-117.

- Bishop, C. A., Petit, K.E., Gartshore, M.E., and D. A. MacLeod. (1997). Extensive monitoring of anuran populations using call counts and road transects in Ontario (1992 to 1993). Pages 149-160 in D. M. Green, editor. *Amphibians in decline, Canadian studies of a global problem, herpetological conservation*. Volume 1. Society for the Study of Amphibians and Reptiles, St. Louis, Missouri, USA.
- Bonin J., Desgranges, J-L., Rodrigue, J., and M. Ouellet. (1997a) Anuran species richness in agricultural landscapes of Quebec: foreseeing long-term results of road call surveys. In: Green DM (ed) *Amphibians in decline: Canadian studies of a global problem*. Society for the Study of Amphibians and Reptiles, St. Louis, Missouri, USA, pp 141–149.
- Bonin, J., Ouellet, M., Rodrigue, J., DesGranges, J-L., Gagne, E., Sharbel, T.E., and L. A. Lowcock. (1997b). Measuring the health of frogs in agricultural habitats subjected to pesticides. Pages 246-257 in D. M. Green, editor. *Amphibians in decline: Canadian studies of a global problem*. Society for the Study of Amphibians and Reptiles, St. Louis, Missouri, USA.
- Boone, M.D. and C.M. Bridges-Britton. (2006). Examining multiple sublethal contaminants on the gray treefrog (*Hyla versicolor*): effects of an insecticide, herbicide, and fertilizer. *Environmental Toxicology and Chemistry*, 25.12:3261-3265.

- Boscolo, D. and J.P. Metzger. (2009). Is bird incidence in Atlantic forest fragments influenced by landscape patterns at multiple scales?. *Landscape Ecology*, 24.7:907-918.
- Boutin, C. L. and B. T. Jobin. (1998). Intensity of Agricultural Practices and Effects on Adjacent Habitats. *Ecological Applications*, 8:544-557.
- Burgett, A. A., Wright, C.D., Smith, G.R., Fortune, D.T., and S.L. Johnson. (2007). Impact of ammonium nitrate on wood frog (*Rana sylvatica*) tadpoles: effects on survivorship and behavior. *Herpetological Conservation and Biology*, 2.1:29-34.
- Bury, R.B. and J.A. Whelan. (1984). Ecology and management of the bullfrog. U.S. Fish and Wildlife Service, Resource Publication Number 155, Washington, D.C.
- Canadian Council of Ministers of the Environment (2003). Canadian water quality guidelines for the protection of aquatic life: nitrate ion. CCMI, Winnipeg.
- Chapin, J. W. and J.S. Thomas. (2003). Burrower bugs (Heteroptera: Cydnidae) in peanut: seasonal species abundance, tillage effects, grade reduction effects, insecticide efficacy, and management. *Journal of economic entomology*, 96.4:1142-1152.
- Collins, J.T. (1993). Amphibians and reptiles in Kansas. Third edition, revised. Natural History Museum, University of Kansas, Lawrence, Kansas.
- Conant, R. and J.T. Collins. (1998). A Field Guide to Amphibians and Reptiles: Eastern and Central North America. Third edition, expanded. Houghton Mifflin Company, Boston, Massachusetts.

- Cushman, (2006). Effects of habitat loss and fragmentation on amphibians: A review and prospectus. *Biological Conservation*, 128:231-240.
- Dayton, G. H. and L. A. Fitzgerald. (2001). Competition, predation, and the distributions of four desert anurans. *Oecologia*, 129:430-435.
- de Wijer P., Watt, P.J. and R.S. Oldham. (2003). Amphibian decline and aquatic pollution: effects of nitrogenous fertilizer on survival and development of larvae of the frog *Rana temporaria*. *Applied Herpetology*. 1:3-12.
- Donald, P.f., Sanderson, F.J., Burfield, I.J., and F.P.J. van Bommel. (2006). Further evidence of continent-wide impacts of agricultural intensification on European farmland birds, 1990–2000. *Agriculture, Ecosystems and Environment*, 116:189-196.
- Dunn, A. M., Julien, G., Ernst, W. R., Cook, A., Doe, K. G., and P.M. Jackman (2011). Evaluation of buffer zone effectiveness in mitigating the risks associated with agricultural runoff in Prince Edward Island. *Science of the Total Environment*, 409.5:868-882.
- Ecobichon, D. J. (2001). Pesticide use in developing countries. *Toxicology*, 160.1:27-33.
- Elliott, N. C., Kieckhefer, R. W., Lee, J. H., and B.W. French. (1999). Influence of within-field and landscape factors on aphid predator populations in wheat. *Landscape Ecology*, 14.3:239-252.
- Eigenbrod, F., Hecnar, S. J., and L. Fahrig. (2008). The relative effects of road traffic and forest cover on anuran populations. *Biological conservation*, 141.1: 35-46.

Fort, D.J., Guiney, P.D., Weeks, J.A., Thomas, J.H., Rogers, R.L., Noll, A.M., and C.D.

Spaulding. (2004). Effect of methoxychlor on various life stages of *Xenopus laevis*. *Toxicological Sciences*, 81:454-466.

Gagné, S.A. and L. Fahrig. (2007). Effect of landscape context on anuran communities in breeding ponds in the National Capital Region, Canada. *Landscape Ecology*, 22:205-215.

Geiger, F., Bengtsson J, Berendse F, Weisser W, Emmerson M, Morales MB, Ceryngier P, Liira J, Tscharntke T, Winqvist C, Eggers S, Bommarco R, Part T, Bretagnolle V, Plantegenest M, Clement L, Dennis C, Palmer C, Onate JJ, Guerrero I, Hawro V, Aavik T, Thies C, Flohre A, Hanke S, Fischer C, Goedhart PW, and P. Inchausti. (2010). Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. *Basic and Applied Ecology*, 11.2:97-105.

Gibbs, J.P., Breisch, A.R., Ducey, P.K., Johnson, G., Behler, J.L., and R.C. Bothner. (2007). The amphibians and reptiles of New York state. Oxford University Press, New York. xv + 422 pp.

Gray, M.J., Smith, L.M., and R. Brenes. (2004). Effects of agricultural cultivation on demographics of Southern High Plains amphibians. *Conservation Biology* 18.5:1368-1377.

Green, N.B. and T.K. Pauley. (1987). Amphibians and Reptiles in West Virginia. University of Pittsburgh Press, Pittsburgh, Pennsylvania.

- Guerry, A.D., and M.L. Hunter. (2002). Amphibian distributions in a landscape of forests and agriculture: an examination of landscape composition and configuration. *Conservation Biology*, 16.3:745-754.
- Hamer, A.J., Makings, J.A., Lane, S.J., and M.J. Mahoney. (2004). Amphibian decline and fertilizers used on agricultural land in south-eastern Australia. *Agriculture, ecosystems & environment*, 102.3: 299-305.
- Hammerson, G. A. (1999). Amphibians and reptiles in Colorado. Second edition. University Press of Colorado, Boulder. xxvi + 484 pp.
- Hazell, D. (2003). Frog ecology in modified Australian landscapes: a review. *Wildlife Research*, 30:193-205.
- Hecnar, S.J. (1995). Acute and chronic toxicity of ammonium nitrate fertilizer to amphibians from southern Ontario. *Environmental toxicology and chemistry* 14.12:2131-2137.
- Hecnar, S.J. (2004). Great Lakes wetlands as amphibian habitats: a review. *Aquatic Ecosystem Health & Management*, 7.2:289-303.
- Hecnar, S.J. and R.T. M'Closkey. (1996). Regional dynamics and the status of amphibians. *Ecology*, 77:2091-97.
- Hecnar, S.J. and R.T. M'Closkey. (1997). Changes in the composition of a ranid frog community following bullfrog extinction. *American Midland Naturalist*, 137.1:145-150.

- Hirao, T., Murakami, M., Iwamoto, J., Takafumi, H., and H. Oguma. (2008). Scale-dependent effects of windthrow disturbance on forest arthropod communities. *Ecological research*, 23.1:189-196.
- Hocking, D. J. and R. D. Semlitsch. (2007). Effects of timber harvest on breeding-site selection by gray treefrogs (*Hyla versicolor*). *Biological Conservation*, 138:506–13.
- Holland, J.D., Bert, D.G. and L. Fahrig. (2004) Determining the spatial scale of species' response to habitat. *Bioscience*, 54:227–233.
- Hoff, K.V.S., A.R. Blaustein, R.W. McDiarmid and R. Altig. (1999). Behavior: interactions and their consequences. Pp. 125–239. In McDiarmid, R.W. and R. Altig (Eds.), *Tadpoles: The Biology of Anuran Larvae*. University of Chicago Press, Chicago, Illinois.
- Huey, D.W., and T.L. Beitinger. (1980). Hematological responses of larval *Rana catesbiana* to sublethal nitrite exposures. *Bulletin of environmental contamination and toxicology*, 25.1:574-577.
- Johnson, J.R. (2005). Multi-scale investigations of gray treefrog movements: patterns of migration, dispersal, and gene flow (Doctoral dissertation, University of Missouri--Columbia).
- Klemens, M.W. (1993). *Amphibians and reptiles of Connecticut and adjacent regions*. State Geological and Natural History Survey of Connecticut, Bulletin Number 112, Hartford, Connecticut.

- Knutson, M. G., Sauer, J. R., Olsen, D. A., Mossman, M. J., Hemesath, L. M., and M.J. Lannoo. (1999). Effects of landscape composition and wetland fragmentation on frog and toad abundance and species richness in Iowa and Wisconsin, USA. *Conservation Biology*, 13.6:1437-1446.
- Knutson, M.G., Richardson W.B., Reineke D.M., Gray B.R., Parmelee J.R., and S.E. Weick. (2004). Agricultural ponds support amphibian populations. *Ecological Applications*, 14:669–684.
- Krishnamurthy, S.V., Meenakumari, D., Gurushankara, H.P., and V. Vasudev. (2008). Nitrate-induced morphological anomalies in the tadpoles of *Nyctibatrachus major* and *Fejervarya limnocharis* (Anura: Ranidae). *Turkish Journal of Zoology*, 32:239-244.
- Kuhn, A., Copeland, J., Cooley, J., Vogel, H., Taylor, K., Nacci, D., and P.V. August. (2011). Modeling Habitat Associations for the Common Loon (*Gavia immer*) at Multiple Scales in Northeastern North America.
- Land Information Ontario. 2010. NRVIS/OLIW Data Management Model For Wetland Unit. Available Online: <http://www.ontario.ca/environment-and-energy/land-information-ontario> [Accessed: 13 December 2012].
- Lannoo, M.J. (1996). Okoboji Wetlands: A Lesson in Natural History. University of Iowa Press, Iowa City, Iowa.
- Le Féon, V., Schermann-Legionnet, A., Delettre, Y., Aviron, S., Billeter, R., Bugter, R., Hendrickx, F., and F. Burel. (2010). Intensification of agriculture, landscape

- composition and wild bee communities: a large scale study in four European countries. *Agriculture, Ecosystems and Environment*, 137:143–150
- Lehtinen, R. M., and S.M. Galatowitsch. (2001). Colonization of restored wetlands by amphibians in Minnesota. *The American Midland Naturalist*, 145.2:388-396.
- Leibold M.A. and H.M. Wilbur. (1992). Interactions between food-web structure and nutrients on pond organisms. *Nature*, 360:341–343.
- Loman, J. and B. Lardner. (2006). Does pond quality limit frogs *Rana arvalis* and *Rana temporaria* in agricultural landscapes? A field experiment. *Journal of Applied Ecology*, 43.4:690-700.
- Maberly S.C., King L., Dent M.M., Jones R.I. and C.E. Gibson. (2002). Nutrient limitation of phytoplankton and periphyton growth in upland lakes. *Freshwater Biology*, 47:2136 – 2152.
- Mazerolle, M.J. (2001). Amphibian activity, movement patterns, and body size in fragmented peat bogs. *Journal of Herpetology*, 35:13–20.
- McAllister, K.L., W.P. Leonard, D.W. Hays, and L.C. Friesz. (1999). Washington State status report for the Northern Leopard Frog. Washington Department of Fish and Wildlife, Olympia, Washington. 36pp.
- Merrell, D. J. (1977). Life history of the leopard frog, *Rana pipiens*, in Minnesota. Occasional Paper Number 15. Bell Museum of Natural History. University of Minnesota, Minneapolis, Minnesota, USA.

Minton, S.A., Jr. (2001). *Amphibians and Reptiles of Indiana*. Second edition. Indiana Academy of Science, Indianapolis, Indiana.

OHN Ontario Hydro Network. (2011). Ontario Hydro Network - Waterbody. Available Online: <https://www.ontario.ca/environment-and-energy/ohn-waterbody> [Accessed: 12 December 2012].

OMAFRA Ontario Ministry of Agriculture Food & Rural Affairs. (2010). Agricultural Resource Inventory. Available Online: http://www.omafra.gov.on.ca/english/landuse/gis/ari_1983.htm [Accessed: 1 January 2013].

Orton, Frances, James A. Carr, and Richard D. Handy. (2006). Effects of nitrate and atrazine on larval development and sexual differentiation in the northern leopard frog *Rana pipiens*. *Environmental Toxicology and Chemistry* 25.1: 65-71.

Ouellet, M., J. Bonin, J. Rodrigue, J. DesGranges, and S. Lair. (1997). Hindlimb deformities (ectromelia, ectrodactyly) in free-living anurans from agricultural habitats. *Journal of Wildlife Diseases*, 33:95-104.

Patrick, D. A., Hunter Jr, M. L., and A.J. Calhoun. (2006). Effects of experimental forestry treatments on a Maine amphibian community. *Forest Ecology and Management*, 234(1), 323-332.

Pauley, T. K., and M.J. Lannoo. (2005). *Rana clamitans* Latreille, 1801; Green Frog. *Amphibian Declines: The Conservation Status of United States Species*. University of California Press, Los Angeles, California, 549-552.

- Petraitis, P. S., A. E. Dunham, and P. H. Niewiarowski. (1996). Inferring multiple causality: the limitations of path analysis. *Functional Ecology*, 10:421–431.
- Petranka, J.W. and D.A.G. Thomas. (1995). Explosive breeding reduces egg and tadpole cannibalism in the wood frog, *Rana sylvatica*. *Animal Behavior*, 50:731–739.
- Pope, S. E., Fahrig, L., and H.G. Merriam. (2000). Landscape complementation and metapopulation effects on leopard frog populations. *Ecology*, 81.9:2498-2508.
- Quammen J.K., Durtsche R.D. (2003): Diet comparisons in three tadpole species, *Rana sylvatica*, *Bufo americanus*, and *Pseudacris crucifer*, in a northern temperate climate. *Norse Scientist* 1:45-50.
- Redmer, M. (2002). Natural history of the wood frog (*Rana sylvatica*) in the Shawnee National Forest, southern Illinois. *Illinois Natural History Survey Bulletin* 36:163–194.
- Relyea R. (2005). The lethal impact of Roundup on aquatic and terrestrial amphibians. *Ecological Applications*, 15:1118–1124.
- Relyea, R. A., J. E. Elliott, C. A. Bishop, and C. A. Morrissey. (2011). Amphibians Are Not Ready for Roundup. *Wildlife Ecotoxicology*, pp 267-300. Springer New York.
- Rouse, J. D., Bishop, C. A., and J. Struger. (1999). Nitrogen pollution: an assessment of its threat to amphibian survival. *Environmental health perspectives*, 107.10: 799.
- Sala, O. E., F. Stuart Chapin , III, J. J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L. F. Huenneke, R. B. Jackson, A. Kinzig, R. Leemans, D. M. Lodge, H. A.

- Mooney, M. n. Oesterheld, N. L. Poff, M. T. Sykes, B. H. Walker, M. Walker, and D. H. Wall. (2000). Global Biodiversity Scenarios for the Year 2100. *Science*, 287:1770-1774.
- Schreinemachers, P. and P. Tipraqsa. (2012). Agricultural pesticides and land use intensification in high, middle and low income countries. *Food Policy*, 37(6), 616-626.
- Schwartz, J. J., Bee, M. A., and S.D. Tanner. (2000). A Behavioral and Neurobiological Study of the Responses of Gray Treefrogs, *Hyla versicolor* to the Calls of a Predator, *Rana catesbeiana*. *Herpetologica*, 27-37.
- Shipley, B. (2002). *Cause and correlation in biology: a user's guide to path analysis, structural equations and causal inference*. Cambridge University Press.
- Shriar, A. J. (2000). Agricultural intensity and its measurement in frontier regions. *Agroforestry Systems*, 49.3:301-318.
- Smith, G.R., (2007). Lack of effect of nitrate, nitrite and phosphate on wood frog (*Rana sylvatica*) tadpoles. *Applied Herpetology* 4:287-291.
- Smith, G. R., and C.J. Dibble. (2012). Effects of an invasive fish (*Gambusia affinis*) and anthropogenic nutrient enrichment on American toad (*Anaxyrus americanus*) tadpoles. *Journal of Herpetology*, 46.2:198-202.
- Smith, A.M. and D. M. Green. (2005). Dispersal and the metapopulation paradigm in amphibian ecology and conservation: are all amphibian populations metapopulations? *Ecography*, 28:110-128.

- Stoate, C., Boatman, N. D., Borralho, R. J., Carvalho, C., De Snoo, G. R., and P. Eden. (2001). Ecological impacts of arable intensification in Europe. *Journal of environmental management*, 63.4:337-365.
- Storer, T.I. (1922). The eastern bullfrog in California. *California Fish and Game*, 8:219–224.
- Thomson, L.J., McKenzie, J., Sharley, D.J., Nash, M.A., Tsitsilas, A., and A.A. Hoffmann. (2010). Effect of woody vegetation at the landscape scale on the abundance of natural enemies in Australian vineyards. *Biological Control*, 54.3:248-254.
- Travis, J. (1981). Control of larval growth variation in a population of *Pseudacris triseriata* (Anura: Hylidae). *Evolution*, 423-432.
- Venter, O., Brodeur, N.N., Nemiroff, L., Belland, B., Dolinsek, I.J. and J. W.A. Grant. (2006). Threats to Endangered Species in Canada. *BioScience*, 56:903-910.
- Wiens, J.A. (1989) Spatial scaling in ecology. *Functional Ecology*, 3:385–397.
- Werner, E. E. and M.A. McPeck. (1994). Direct and indirect effects of predators on two anuran species along an environmental gradient. *Ecology*, 75:1368-1382.
- Whitaker, J.O. Jr. (1971). A study of the Western Chorus Frog, *Pseudacris triseriata*, in Vigo County, Indiana. *Journal of Herpetology* 5(3-4):127-150.
- Whiting, A. (2004). Population ecology of the Western Chorus Frog, *Pseudacris triseriata*. M.Sc. Thesis, McGill University, Montréal, Québec, Canada. 106 pp.

- Wright, A.H. (1932). Life Histories of the Frogs of the Okefinokee Swamp, Georgia. North American Salientia (Anura) Number 2. Macmillan Press, New York.
- Wright, A.H. and A.A. Wright. (1949). Handbook of Frogs and Toads of the United States and Canada. Third edition. Comstock Publishing Associates, Ithaca, New York.
- Wilcove DS, Rothstein D, Dubow J, Phillips A, and E. Losos. (1998). Quantifying threats to imperiled species in the United States. *BioScience*, 48:607–615.

Appendices

Appendix 1

Appendix 1: Generalized linear model output for effects of landscape predictors on anuran abundance (8 sp) in Eastern Ontario (39 ponds), in which β -coefficient values are displayed at 6 scales: 100, 250, 500, and 1000, 2000, and 4000 m. Only 250, 500, and 1000 m scales were considered for later analyses because of high landscape predictor correlations between crop cover and habitat at other scales.

Appendix 2

Appendix 2: Proportion of landscape cover types at all scales surrounding ponds (39) in the agricultural region of Eastern Ontario. Low-intensity agricultural cover (lo) consisted mostly of perennial crops, while high-intensity agricultural cover (hi) consisted of row crops. The other two landscape predictors were forest (fo) and wetland (we) cover.

Appendix 3

Appendix 3: Raw pond data (2013 data) from 4 anuran call surveys. See Methods section for details.

Site	Wat. Temp. (°C)	pH	Conductivity	Depth (m)	Water Clarity	% Overhanging Vegetation	% Open Water	% Submerged Vegetation	% Emerging Vegetation	% Float. Veg.
3	13	8.28	517	1.20	100	5	95	5		
5	11.1	9.71	933	0.60	25	8	45	35	20	
9	22.3	8.9	527	0.85	100	1	80	5	15	
11	10.8	8.48	330	1.58	100	10	90	5	5	
14	12.9	10.2	1710	0.75	100	0	60	30	10	
19	12	10.2	63	0.60	100	10	40	30	20	10
20	10.6	8.12	352	1.01	100	5	40	20	15	5
22	14.9	7.97	405	1.22	100	5	5	35	60	
23	14.6	11.1	313	0.48	100	1	95		5	
24	12.7	10.1	125	1.70	50	0	75	10	10	5
28	12.5	9.96	246	0.60	90	85	90	5	5	
29	13.4	10.5	526	0.90	100	2	90	8	2	
30	11.3	11	530	0.85	100	1	70	20	10	
31	9.9	10.3	162	0.75	100	1	20	60	20	
32	18.1	10.7	393	0.99	100	3.5	35	35	30	
35	20.7	9.22	541	0.35	100					
38	7.9	9.8	283	0.48	100	5	50	30	20	
41	14.3	7.65	298	0.75	40	2	95	2.5	2.5	
42	14.6	10.2	418	0.99	80	6	90	3	7	
43	12.9	9.82	410	0.55	100	0	80	20	0	0
44	14.2	8.8	428	1.38	20	2	95	8	8	5
45	12.6	9.87	296	1.06	40	5	85	5	5	5

52	11.6	10.5	365	0.74	100	4	30	40	30	
55	18.8	10.5	428	0.80	100	9	30	30	40	
61	12.01	7.1	712	1.06	50	25	15	20	40	25
64	15.5	12.6	225	1.54	50	1	95	5		
66	18.9	12.2	295	0.94	30	3	98	1	1	
67	18.2	11.1	719	1.34	50	97	2	1		
69	18.2	10.6	299	0.81	100	5	90	5	5	
71	15.5	10.4	706	1.68	75	1	88	10	2	
72	20.6	10.8	701	0.70	50	3	20	10	20	
73	14.9	10.1	843	0.92	100	1	95	5		
77	18.7	10.4	520	0.58	75	0	10	40	40	10
79	20.4	10.3	550	0.71	100	3	33	33	33	
81	12.5	10.6	95	1.13	42	2	60	20	10	10
102	20.3	8.55	629	0.25	70	95	0	90	90	
129	21.6	10.8	967	1.93	35	2	90		10	
159	20.9	11.1	570	0.90	80	0.5	95	35	25	
173	21	10.1	400	0.85	80	2	95	5		
3	16	8.75	565	1.05	100	7	95	2.5	2.5	
5	18.7	8.12	668	0.61	25	12	60	20	20	
9	18	9.3	244	0.78	100	8	80		20	
11	14.2	7.41	325	1.38	100	6	95	2.5	2.5	
14	21	7.4	111	0.64	100	0	95		5	
19	14.2	10.3	96	0.52	100	8	40	20	20	20
20	15.6	9.05	449	0.86	100	5	90		10	
22	21.2	10.4	219	0.94	100	30	85	5	10	
23	18.1	7.07	504	0.42	100	2	95	2.5	2.5	
24	14.4	10.2	134	1.47	44	0	60	10	20	10
28	17.8	9	228	0.51	90	90	90	5	5	
29	11.3	7.96	496	0.65	100	7	60	20	20	

30	13.8	10.5	517	0.53	100	2	90	2	8	
31	17.2	8.34	239	0.64	100	1	60		40	
32	19	9.74	386	0.85	100					
35	19.2	10.6	468	0.30	100					
38	19	7.17	870	0.42	100	0				100
41	22.2	9.93	293	0.66	40	10	70	10	15	5
42	13.9	8.08	356	0.76	80	6	95		5	
43	15.3	9.78	482	0.48	100	2	0	60	40	
44	15.3	9.14	391	1.19	20	2	95	2.5	2.5	
45	14	7.8	470	0.92	40	10	50	20	30	
52	19.2	10.5	312	0.64	100	5	20	40	40	
55	11.8	8.7	406	0.70	100	9	5	30	65	
61	13.7	7.85	717	0.89	50	4	5	40	55	
64	18.9	11.9	257	1.33	50	3	95	5		
66	19.2	10.4	302	0.82	50	5	100			
67	19.4	10.4	513	1.15	50	9			100	
69	16.4	8.53	403	0.70	100	1	20	20	60	
71	15.2	7.35	649	1.45	75	5	60	30	10	
72	19	6.67	501	0.60	50	3	20	30	30	20
73	15.1	8.15	762	0.80	100					
77	22.9	8.89	621	0.50	75	7		20	80	
79	20.4	5.6	624	0.62	100	4	20	20	60	
81	14.6	9.93	158	0.97	42	2	60	20	10	10
102	20.9	9.89	797	0.22	70	8	95	5		
129	21.4	9.85	169	1.77	35	1	80	10	10	
159	22.9	9.87	497	0.81	80	2	90	5	5	
173	21	10.4	341	0.83	80	7	90			10
3	19.9	9.09	449	0.83	100	10	70	10	20	
5	21	9.76	737	0.39	25	30			100	

9	25.1	7.98	437	0.66	100	1			15	85
11	18	8.46	345	0.95	100	6	80	5	10	5
14	24.5	9.79	1693	0.50	100	0	20	10	30	40
19	17.1	10.1	110	0.41	100	9	35	15	30	20
20	22.6	9.23	542	0.68	100	2	100			
22	26.8	9.94	396	0.75	100	8	20	20	60	
23	26.5	9.21	212	0.33	100	8	85	5	5	5
24	18.4	9.98	134	1.16	40	0	50	10	25	15
28	22.9	9.77	306	0.40	90	90	95		5	
29	22.3	10.5	464	0.55	100	6	80	10	10	
30	22.6	9.28	467	0.50	100	3	70	10	10	10
31	20.4	10.1	153	0.50	100	70			90	10
32	26.1	9.24	175	0.67	100	9	20		10	70
35	22.9	8.89	621	0.24	100	7		20	80	
38	25.9	10.8	256	0.33	100	5	10	10	40	40
41	29.3	10	284	0.48	30	7	80	10	10	
42	22.3	10.1	421	0.68	80	8	85		15	
43	18.3	8.94	463	0.38	100	0	30	10	60	
44	20.1	9.51	378	0.94	20	2	90	5	5	
45	19.6	8.23	244	0.72	30	10	10	30	60	
52	26	8.12	428	0.50	100	0	0	50	50	
55	23.6	9	437	0.55	100	7		10	90	
61	17.2	9.04	500	0.70	45	5	15	80		
64	25.8	9.19	283	1.05	50	5	95	5		
66	24.5	10.2	324	0.64	30	15	95		5	
67	24.1	9.42	536	0.91	50	9			10	
69	24.9	8.58	442	0.60	100	3		50	50	
71	25.3	8.97	600	1.15	75	5	60	30	10	
72	22.1	9.79	493	0.45	50	3	10		40	50

73	24.6	10.8	647	0.65	100	2	90	5		5
77	23.1	9.13	697	0.40	75	7		10	90	
79	23.3	9.35	696	0.49	100	3	5	5	90	
81	19.2	10.2	345	0.77	42	2	50	20	20	10
102	24.3	9.45	746	0.17	70	6	90	5	5	
129	22.1	9.05	793	1.20	35	0	85	5	10	
159	26.3	8.8	532	0.67	80	1	90	5	5	
173	25.1	10.3	265	0.65	80	2	90	5		5
3	27.6	8.75	282	0.69	100	8	40	10	20	30
5	22.4	9.45	761	0.32	25	6			100	
9	25.6	9.54	196	0.49	100	2	30		70	
11	27.2	9.71	288	0.74	100	35	60	10	20	10
14	22	10.1	1695	0.40	100	0	20		20	60
19	21.5	9.43	93	0.33	100	30		5	80	5
20	24.6	9.19	328	0.54	100	4	90		10	
22	25.7	9.79	412	0.45	100	7	14	25	60	
23	20.6	10.3	481	0.26	100					
24	24.6	10.5	168	0.93	30	0	60	10	20	10
28	23.4	9.62	327	0.32	90	95	95		5	
29	26.5	10.6	468	0.39	100	7	80	10	10	
30	26	9.44	462	0.40	100	2	80	10	10	
31	19.4	10.2	400	0.40	100	3		5	90	5
32	26.5	9.34	316	0.54	100	10	10		20	70
35	23.2	8.97	658	0.19	100	3			100	
38	23.8	10	244	0.26	100	2	5		5	90
41	28.9	9.9	298	0.41	30	8	80	10	10	
42	24.8	10.8	437	0.54	80	8	80		10	10
43	22.6	8.45	468	0.30	100	0	80		20	
44	26.9	9.92	383	0.75	20		80		5	15

45	29.4	8.36	223	0.58	30	3	30	40	30	
52	23.5	8.64	589	0.40	100	3	90	5	5	
55	24.3	8.8	206	0.44	100	40			100	
61	27.7	8.87	668	0.62	40	2	0	20	80	
64	25.4	11.3	288	0.84	50	2	99			1
66	23.8	8.98	590	0.52	15	10			100	
67	24.2	8.98	549	0.68	50	9	25	5		70
69	23.6	10.6	514	0.44	100	0	0	40	60	0
71	29.1	9.12	632	0.92	75	6	60	20	10	10
72	19.2	9.01	562	0.38	50	2			30	70
73	27.3	11	646	0.50	100	3	90			10
77	25.6	8.93	418	0.31	75	6		10	90	
79	19.5	9.11	624	0.39	100	2		40	60	
81	23.9	11.6	155	0.62	42	2	90	10		
102	24.6	9.49	700	0.15	70	2	90		10	
129	23.1	9.59	163	1.06	35	0	50	20	30	
159	24.4	9.66	524	0.50	80	1	99			1
173	24.6	10.1	258	0.52	80	2	98			2

Appendix 4

Appendix 4: Raw call survey data for the abundance of each anuran taken with 10-minute chorus. We used the following abundance classes: 0 (no calls), 1 (distinct calls of separate individuals), 2 (some calls overlap but most individuals can still be identified), 3 (mostly overlapping calls and continuous calling) (see methods for more information). Estimated actual abundance was also noted in parentheses, but we did not use this data because we felt it was less reliable than ranks.

Site	Survey	Date	Start Time	<i>P. cruc.</i>	<i>A. amer.</i>	<i>P. tris.</i>	<i>H. vers.</i>	<i>L. pipi.</i>	<i>L. cate.</i>	<i>L. clam.</i>	<i>L. sylv.</i>
44	1	4-15-13	20:34								
81	1	4-15-13	22:00	1		3				1	
19	1	4-15-13	22:31	2		3					1
24	1	4-15-13	22:57	3							
61	1	4-17-13	20:43	3							1 (12)
11	1	4-17-13	21:05	2 (20)							1 (3)
45	1	4-17-13	22:37					1			1
3	1	4-23-13	20:44	2 (15)							1 (1)
30	1	4-23-13	22:45								
43	1	4-23-13	23:27	3		2 (16)		1			1
31	1	4-26-13	21:55	2 (18)				1 (4)			1 (3)
14	1	4-26-13	23:15								1 (1)
38	1	4-26-13	23:40	2 (20)							
5	1	4-26-13	21:01	3							1 (3)
73	1	4-29-13	22:44								
42	1	4-29-13	21:41	3				1 (5.5)			
29	1	4-29-13	22:19	2 (20)				1			
71	1	4-29-13	23:29								

69	1	4-30-13	22:29	3	3			1			
64	1	4-30-13	22:53	2 (8)	1						
23	1	4-30-13	23:31	2.5 (25)	3						
67	1	5-3-13	22:54		2						1
52	1	5-3-13	23:51	2 (19)				1 (1)			
66	1	5-3-13	22:28		2 (11)						
32	1	5-4-13	22:28	2 (13)	1 (3)			1 (1)		1 (3)	
35	1	5-4-13	21:08	2 (22)		2 (25)		1 (2)			
9	1	5-5-13	20:44	3 (30)		2 (10)	1 (2)				
20	1	5-5-13	21:52	3 (28)		2					1
55	1	5-5-13	21:57	3 (25)				1 (7)			
77	1	5-5-13	22:30	2 (20)			1 (1)				
72	1	5-6-13	23:20	1 (1)							
79	1	5-6-13	23:38	2 (10)			1 (2)				
102	1	5-7-13	21:34	1 (3)							
173	1	5-7-13	22:15		2 (12)		2 (14)	1 (1)			
129	1	5-7-13	22:49	1 (3)	1 (2)			1 (1)			
159	1	5-7-13	23:28	1 (2)	2 (18)					1 (1)	
28	1	5-9-13	21:33								
22	1	5-9-13	22:00	1 (1)							
41	1	5-9-13	22:30	1 (3)							
45	2	5-13-13	22:06	1 (2)							
11	2	5-13-13	20:50	1 (1)							
61	2	5-13-13	21:11	1 (6)							
3	2	5-14-13	20:36	1 (3)							
43	2	5-14-13	21:02	2 (16)						1 (1)	

30	2	5-14-13	21:43	1 (1)							
44	2	5-17-13	21:03			1 (1)					
19	2	5-17-13	21:50	1 (1)							
24	2	5-17-13	22:05			1 (2)					
81	2	5-17-13	22:30			1 (2)					
38	2	5-20-13	21:12	2 (13)			1 (2)				
14	2	5-20-13	21:55	1 (8)			1 (4)	1 (1)			
5	2	5-20-13	22:55	2 (22)	1 (4)		3 (30)				
31	2	5-20-13	23:32	1 (9)	1 (5)		1 (5)	1 (7)			1 (1)
73	2	5-24-13	22:08								
71	2	5-24-13	21:05								
29	2	5-24-13	22:25	1 (2)				1 (1)			
42	2	5-24-13	23:10	1 (1)							
64	2	5-25-13	21:22	1 (4)	1 (2)		1 (3)				
69	2	5-25-13	22:18	1 (1)			1 (2)	1 (1)			
23	2	5-25-13	21:48	1 (5)	1 (2)		1 (2)			1 (2)	1 (1)
52	2	5-27-13	21:33								
67	2	5-27-13	22:17		1 (2)		1 (5)	1 (2)			
66	2	5-27-13	22:45		1 (1)						
32	2	6-3-13	22:58	1 (4)							
35	2	6-3-13	23:08	1 (7)				1 (2)			
79	2	6-9-13	21:54				2 (20)				
72	2	6-9-13	23:05							1 (2)	
20	2	6-13-13	22:19							1 (1)	
55	2	6-13-13	22:35	1 (2)			1 (2)			1 (4)	
9	2	6-13-13	23:06	1 (2)			1 (3)			1 (5)	

77	2	6-13-13	23:47			1 (3)			1 (12)	
159	2	6-14-13	21:35			1 (3)			1 (2)	
129	2	6-14-13	22:19					1 (2)	1 (7)	
102	2	6-14-13	23:29						1 (4)	
173	2	6-14-13	22:55	1 (1)		1 (2)	1 (1)		1 (7)	
41	2	6-15-13	21:54			1 (1)			1 (2)	
22	2	6-15-13	22:16			3 (25)				
28	2	6-15-13	22:37			1 (5)				
81	3	6-17-13	22:00	1 (7.5)		3 (25)				
24	3	6-17-13	22:36			2 (18)				
19	3	6-17-13	23:04			2 (18)				
44	3	6-17-13	23:27			1 (2)			1 (2)	
61	3	6-18-13	23:30			1 (1)				
45	3	6-18-13	22:01						1 (2)	
11	3	6-18-13	22:38			1 (1)			1 (2)	
30	3	6-20-13	22:11					1 (2)		
43	3	6-20-13	22:50						1 (1)	
3	3	6-20-13	23:46			3 (25)			1 (6)	
5	3	6-26-13	0:49						1 (3)	
31	3	6-26-13	0:05			1 (3)			2 (10)	
14	3	6-26-13	23:21	1 (3)		1 (6)			1 (4)	
38	3	6-26-13	22:45			1 (10)			1 (5)	
71	3	6-30-13	22:02						1 (1)	
73	3	6-30-13	23:03					1 (5)	1 (1)	
29	3	6-30-13	23:00					1 (1)	1 (1)	
42	3	6-30-13	23:43			1 (1)		1 (2)	1 (5)	

69	3	7-2-13	23:42						1 (4)	
64	3	7-2-13	22:58			1 (7)			1 (5)	
23	3	7-2-13	22:12					1 (1)	1 (10)	
52	3	7-3-13	22:28	1 (1)		1 (3)				
67	3	7-3-13	22:55	1 (2)		1 (7)				
66	3	7-3-13	23:41	1 (5)					1 (4)	
35	3	7-5-13	23:21			1 (3)			1 (11)	
32	3	7-5-13	23:52			1 (4)			1 (5)	
72	3	7-8-13	22:27					1 (1)	1 (4)	
79	3	7-8-13	11:15			1 (1)	1 (1)		1 (2)	
9	3	7-9-13	22:39			1 (5)			1 (5)	
77	3	7-9-13	0:09			1 (3)			1 (13)	
55	3	7-9-13	0:51						1 (5)	
20	3	7-9-13	1:14					1 (2)	1 (1)	
159	3	7-11-13	21:58						1 (2)	
173	3	7-11-13	23:09						1 (5)	
102	3	7-11-13	23:33						1 (1)	
129	3	7-11-13	22:38					1 (3)	1 (2)	
22	3	7-12-13	22:03						1 (2)	
41	3	7-12-13	21:43						1 (2)	
28	3	7-12-13	22:22							
81	4	7-15-13	23:03						1 (1)	
24	4	7-15-13	23:33			1 (5)				
19	4	7-15-13	22:15						1 (2)	
44	4	7-15-13	21:23					1 (1)	1 (2)	
61	4	7-16-13	23:09				1 (1)			

45	4	7-16-13	22:09						1 (6)	
11	4	7-16-13	22:45						1 (5)	
3	4	7-17-13	21:45						1 (5)	
43	4	7-17-13	22:02							
30	4	7-17-13	22:49					1 (1)		
5	4	7-20-13	21:53						1 (1)	
31	4	7-20-13	22:13						1 (10)	
14	4	7-20-13	23:08						1 (4)	
38	4	7-20-13	23:40					1 (1)	1 (5)	
71	4	7-22-13	23:58						1 (4)	
73	4	7-22-13	22:56					1 (5)	1 (4)	
29	4	7-22-13	22:52					1 (1)	1 (3)	
42	4	7-22-13	22:15					1 (2)	1 (8)	
69	4	7-21-13	22:05						1 (4)	
64	4	7-21-13	22:43					1 (2)	1 (12)	
23	4	7-21-13	23:12						1 (10)	
79	4	7-24-13	22:23							
72	4	7-24-13	22:00						1 (2)	
52	4	7-25-13	21:55							
67	4	7-25-13	22:38						1 (3)	
66	4	7-25-13	23:38							
9	4	7-26-13	23:54						1 (5)	
20	4	7-26-13	23:23						1 (1)	
55	4	7-26-13	22:32						1 (5)	
77	4	7-26-13	21:46						1 (8)	
32	4	7-27-13	22:18						1 (6)	

35	4	7-27-13	22:08						1 (2)	
129	4	7-25-13	22:53						1 (6)	
173	4	7-25-13	22:22						1 (5)	
102	4	7-25-13	22:04						1 (3)	
159	4	7-25-13	23:29						1 (1)	
28	4	7-29-13	22:04							
22	4	7-29-13	22:26						1(2)	
41	4	7-26-13	22:49						1 (3)	

Appendix 5

Appendix 5: Raw landscape predictor data for landscapes surrounding Eastern Ontario ponds across 6 scales. Low-intensity agricultural cover (lo) consisted of perennial crops, while high-intensity agricultural cover (hi) consisted of row crops. The other two predictors were forest cover (fo) and wetland cover (we) in the landscapes. (e.g. 'fo100' denotes forest cover within 100 m of the pond).

Site	hi100	hi250	hi500	hi1000	hi2000	hi4000	lo100	lo250	lo500	lo1000	lo2000	lo4000
3	6.43	21.09	13.10	7.53	23.69	21.13		18.20	26.44	25.32	19.51	12.88
5	46.69	50.29	40.11	20.34	9.52	3.52					14.74	12.63
9	100.00	80.13	40.79	17.85	15.44	10.90					1.23	10.64
11	29.62	40.83	37.21	16.51	14.25	26.13			10.05	11.12	14.98	17.67
14	31.12	40.32	34.98	24.11	28.95	17.92	68.88	59.68	65.02	43.36	16.33	20.47
19			11.73	10.60	16.10	8.58	74.10	53.50	46.14	55.43	39.34	32.59
20	71.55	50.95	25.44	6.72	2.43	2.45			5.82	9.66	13.61	21.14
22	13.81	21.84	16.62	4.51	1.18	13.86			50.94	0.28	13.91	13.74
23		29.89	35.55	18.83	29.44	48.42			0.22		6.77	8.35
24	23.78	28.75	14.42	13.97	14.60	6.42	76.22	53.35	50.94	43.46	26.88	22.36
28	54.67	52.04	50.92	27.02	8.56	7.82			0.22	17.64	19.67	14.69
29		2.02	13.17	16.58	7.08	7.94			4.40	7.09	6.96	14.60
30	47.43	38.27	36.78	24.27	6.57	1.61						
31	12.19	31.87	33.69	17.20	6.30	3.04				1.22	5.07	8.47
32	100.00	100.00	80.65	50.22	33.38	21.75					12.57	7.30
35		3.20	11.60	11.16	2.87	2.10	80.69	44.41	20.17	7.29	9.68	4.22
38	36.43	43.53	46.16	27.27	21.79	11.31			0.31	19.57	17.79	21.49
41			6.02	16.65	22.68	16.58		43.48	49.31	27.57	18.30	20.40
42	100.00	93.73	68.93	53.01	38.23	14.02				2.70	13.38	12.61

43	0.31	8.46	14.97	15.89	13.43	20.39		16.27	23.51	16.00	10.52	13.42
44	32.16	37.11	42.13	36.65	21.81	10.26		3.88	20.28	24.02	20.00	13.20
45	82.44	57.76	49.54	45.78	35.47	29.08					5.92	6.43
52			2.00	8.79	9.87	5.38				6.10	15.86	11.53
55			0.37	8.01	8.22	10.00	100.00	100.00	81.27	56.70	31.95	26.09
61			0.28	18.58	19.35	15.96	6.12	57.39	82.64	50.14	33.27	17.35
64	100.00	94.16	88.82	85.25	55.53	32.13						3.81
66	53.64	87.74	85.68	62.21	38.91	18.20			4.31	24.36	23.07	25.70
67			8.98	17.03	7.76	4.20	73.26	69.09	52.89	27.75	9.64	15.29
69	51.60	45.02	46.10	50.99	41.20	28.17	45.97	29.88	18.71	9.88	7.48	11.24
71		0.16	12.84	27.15	19.26	8.86	67.66	58.32	43.06	26.25	18.59	29.67
72			4.55	16.47	7.58	1.95		26.23	39.73	35.51	20.24	7.14
73			2.98	9.28	8.61	5.08		14.45	26.78	12.26	5.29	12.44
77		1.74	19.48	29.37	23.88	9.83					9.96	19.34
79			5.90	10.88	8.91	4.32	12.48	20.97	23.35	11.06	6.62	6.66
81		8.09	16.32	8.08	2.40	2.42	4.27	42.37	48.02	53.75	33.19	16.64
102						10.05	75.05	83.53	84.65	80.89	46.58	34.89
129	66.76	69.52	81.58	72.55	33.37	25.65				0.03	5.96	25.58
159				3.57	5.45	8.88			0.68	14.01	14.73	16.15
173				24.81	24.03	25.23	70.63	59.01	39.86	20.09	36.03	23.03

Site	we100	we250	we500	we1000	we2000	we4000	fo100	fo250	fo500	fo1000	fo2000	fo4000
3	10.56	3.03	3.15	1.26	1.32	1.95	0.00	9.64	12.52	18.52	22.92	29.44
5	10.63	3.88	1.91	2.22	0.86	15.96	53.31	49.71	45.61	46.57	38.12	27.31
9	5.17	2.62	10.93	31.10	32.25	26.78	0.00	2.58	18.42	44.60	39.76	41.40
11	4.22	0.90	0.25	0.27	0.56	2.26	0.00		2.01	24.22	18.20	10.04

14	3.07	0.64	0.18	0.05	0.01	8.67	0.00			12.04	6.83	19.52
19	5.66	1.32	0.38	0.29	0.10	1.12	2.23	9.91	19.10	18.08	17.26	17.59
20	4.43	13.08	18.20	21.12	19.47	15.19	28.45	49.05	63.14	76.95	62.96	51.14
22	6.48	3.43	1.80	0.75	11.74	6.46	0.00		16.74	38.23	29.80	21.06
23	18.99	14.05	4.13	1.47	0.51	1.51	0.00		0.00	3.84	2.77	3.24
24	2.43	0.48	0.13	0.03	1.79	7.62	0.00	15.42	22.15	16.37	7.96	16.84
28	3.33	0.71	0.20	0.12	3.73	16.20	0.00	37.60	0.51	11.42	33.92	32.12
29	4.76	1.06	0.30	0.27	11.51	23.26	65.37	37.60	26.44	11.39	7.43	15.15
30	4.84	1.09	0.99	13.45	24.06	32.53	15.26	29.61	43.34	68.50	87.82	93.54
31	1.68	0.33	0.09	18.63	17.48	22.62	0.00			5.50	10.21	12.25
32	2.48	0.50	0.14	0.04	0.02	0.11	0.00			0.08	6.24	20.98
35	62.60	32.72	21.46	15.31	8.26	13.28	17.91	42.11	57.42	52.94	40.08	33.73
38	5.24	2.50	1.10	0.32	0.25	1.21	0.00			8.84	22.00	31.25
41	7.07	1.54	0.43	0.28	0.07	2.42	0.00	2.09	5.23	7.19	12.28	17.07
42	5.59	1.94	2.10	5.13	5.32	6.72	0.00	6.27	31.07	33.95	30.37	34.09
43	6.69	1.68	0.50	0.14	0.20	1.13	99.69	75.27	54.51	26.22	18.79	15.21
44	6.28	1.53	1.79	10.93	11.60	30.11	0.00		1.24	13.18	27.38	36.63
45	1.78	0.34	0.09	0.02	0.04	0.11	0.00		3.82	10.34	8.72	7.05
52	1.24	0.23	0.06	0.02	4.37	10.02	0.00	7.70	16.14	10.64	12.83	27.39
55	2.10	0.43	3.38	2.26	2.05	2.35	0.00			1.41	18.22	26.45
61	11.02	5.06	1.44	0.39	0.10	2.58	0.00			6.92	11.71	11.78
64	2.95	0.63	0.30	0.38	0.61	0.31	0.00				2.34	12.34
66	3.82	0.80	0.22	0.08	1.08	0.61	46.36	12.26	5.30	3.21	2.51	8.25
67	42.94	34.40	35.44	47.27	56.12	45.48	26.74	30.91	35.64	42.51	47.85	51.06
69	5.04	2.18	1.05	0.28	0.07	10.77	0.00	6.29	7.21	11.75	18.56	20.96
71	32.74	40.30	41.60	34.67	35.72	30.39	0.00			0.13	5.19	2.41
72	1.55	0.30	0.08	0.22	4.25	21.23	0.00			8.08	14.48	22.35

73	4.91	3.92	15.30	19.61	14.40	11.16	28.90	38.85	18.52	7.98	14.86	24.03
77	3.47	1.36	0.60	0.75	0.66	5.81	7.01	24.72	22.08	28.02	24.62	32.36
79	2.23	0.45	0.12	0.11	0.11	3.41	86.53	46.71	13.51	23.64	31.03	45.31
81	4.57	1.01	0.28	0.08	1.61	2.67	0.00		4.54	13.62	29.16	31.10
102						0.14	11.16	8.76	5.82	3.47	1.61	3.15
129					0.58	0.85	0.00				2.72	4.30
159	19.87	4.53	1.21	0.31	0.08	6.59	0.00		9.57	16.74	23.64	33.31
173	9.72	1.87	0.95	1.25	0.38	3.61	0.00		14.65	18.89	10.41	12.20

Appendix 6

Appendix 6. Pearson correlations for potential landscape predictors (measured as percent cover) in 100, 250, 500, 1000, 2000, and 4000 m - radius landscapes. Significant correlations $p < 0.05$ are denoted by * and $p < 0.01$ by **. Low-intensity agricultural cover (lo) consisted of perennial crops, while high-intensity agricultural cover (hi) consisted of row crops. The other two predictors were forest cover (fo) and wetland cover (we) in the landscapes.

	hi100	lo100	we100
lo100	-.329*		
we100	-0.292	.395*	
fo100	-0.168	-0.128	0.034
	hi250	lo250	we250
lo250	-.536**		
we250	-0.248	0.289	
fo250	-0.173	-0.122	0.169
	hi500	lo500	we500
lo500	-.584**		
we500	-0.215	0.136	
fo500	-0.191	-0.168	0.304
	hi1000	lo1000	we1000
lo1000	-.378*		
we1000	-0.14	-0.12	
fo1000	-0.292	-0.306	.395*
	hi2000	lo2000	we2000
lo2000	-0.223		
we2000	-0.301	-0.308	
fo2000	-.438**	-0.2672	.467**
	hi4000	lo4000	we4000
lo4000	-0.054		
we4000	-.501**	-0.234	
fo4000	-.532**	-.408**	.503**

Appendix 7

Appendix 7. Pearson correlation values for correlations between potential landscape predictors and local habitat predictors of anuran abundance in 39 sample ponds in the agricultural region of Eastern Ontario. Low-intensity agricultural cover (lo) consisted of perennial crops, while high-intensity agricultural cover (hi) consisted of row crops. The other two predictors were forest cover (fo) and wetland cover (we) in the landscapes. Boldness indicates absolute Pearson correlation values ≥ 0.3 . Significant correlations of $p < 0.05$ are denoted by *, $p < 0.01$ by **.

	Nit. Conc.	Water Temp.	pH	Elect. Cond.	Depth	Water Clarity	Overha. Veg.	Pond Area	% Open Wat. Cover	% Subm. Veg. Cover	% Emerg. Veg. Cover	% Float. Veg. Cover
hi250	.247	.021	.218	-.184	.255	-.130	-.017	-.036	.308	-.236	-.270	.211
hi500	.327*	.028	.318*	-.176	.277	-.206	-.015	-.011	.290	-.246	-.248	.109
hi1000	.335*	.176	.374*	-.122	.386*	-.370*	-.140	-.080	.229	-.221	-.219	-.003
lo250	-.155	.055	-.039	.202	-.046	-.074	.106	-.060	-.300	.188	.271	.044
lo500	-.159	.006	-.140	.242	-.009	-.122	.099	-.044	-.288	.238	.219	.037
lo1000	-.124	-.153	-.022	.107	-.096	-.188	.122	-.087	-.119	.171	.073	.049
we250	-.009	.167	-.107	.205	.130	.032	.123	.276	-.186	-.063	.183	.116
we500	-.044	.175	-.104	.220	.232	.055	.111	.130	-.108	-.122	.088	.206
we1000	-.009	.100	-.044	.126	.220	.064	.134	.059	-.055	-.196	.079	.358*
fo250	-.081	-.226	-.065	.200	-.328*	.185	.025	-.088	-.073	.054	.216	-.230
fo500	-.101	-.176	.002	.091	-.246	.184	-.080	-.015	-.094	.000	.232	-.132
fo1000	-.057	-.115	-.132	.073	-.163	.207	.010	-.009	-.081	-.109	.196	.048

Appendix 8

Appendix 8. The Cadmium Reduction Method for determining nitrate concentration (see APHA, 1998).

We collected samples in 500 mL glass jars, which we brought to the lab on each night of sampling and refrigerated at temperatures below 6 °C. During the day following sampling, we brought samples to room-temperature and used de-ionized water to get a reagent blank value on the spectrophotometer. We used a Hanna Instrument handheld tester (HI98129) to check if pH was between 7 and 9 and added HCl or NaOH solution, as necessary, if the pH was outside of this range. We measured absorbance at a 543-nanometer wavelength, which is used to detect complexed cadmium-nitrates. We added one high range nitrate reagent sachet (cadmium-based; used for detecting 0-30 mg/L nitrate;) to each of three 10 mL subsamples from each jar, placed stoppers on each subsample, and shook each vigorously for one minute. Each subsample was then left for 5-minutes for reactions to occur. We took absorbance readings three times per subsample and used a standard curve, built with stock solution and the same spectrophotometer, to calculate the equivalent concentration of nitrate for each absorbance reading in μM . We then averaged nitrate concentrations from each site and converted them from μM to mg/L.

Appendix 9

Appendix 9. Raw nitrate absorbance data for 39 ponds sampled from April-July, 2013.
Note, actual nitrate concentration peaked at 4.95 mg/L in one pond in July.

Site	April-May (absorbance)			June-July (absorbance)			Average Concentration (mg/L)
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	
3	0.043	0.036	0.020	0.036	0.027	0.043	1.06
5	0.048	0.054	0.038	0.014	0.045	0.019	1.10
9	0.036	0.022	0.052	0.020	0.026	0.015	0.86
11	0.035	0.037	0.049	0.180	0.178	0.180	2.99
14				0.028	0.015	0.030	0.76
19	0.033	0.020	0.032	0.018	0.019	0.007	0.56
20	0.022	0.029	0.031	0.100	0.091	0.082	1.72
22	0.009	0.011	0.009	0.022	0.012	0.027	0.52
23	0.076	0.087	0.078	0.026	0.033	0.027	1.66
24	0.022	0.012	0.006				0.43
28	0.024	0.015	0.001	0.023	0.007	0.027	0.56
29	0.031	0.033	0.052	0.022	0.011	0.029	0.80
30	0.049	0.033	0.046	0.029	0.043	0.019	0.96
31	0.071	0.084	0.068	0.027	0.031	0.039	1.68
33				0.034	0.025	0.031	0.53
35	0.065	0.067	0.065	0.018	0.024	0.030	1.41
38	0.053	0.035	0.047				1.06
41	0.032	0.037	0.039	0.023	0.039	0.011	0.93
42	0.024	0.017	0.003				0.56
43	0.067	0.058	0.071	0.022	0.033	0.029	1.26
44	0.067	0.086	0.072	0.026	0.023	0.041	1.48
45	0.017	0.027	0.015	0.020	0.022	0.012	0.55
52	0.030	0.031	0.019	0.023	0.040	0.032	0.79
55	0.004	0.003	0.014	0.080	0.105	0.075	1.46
61	0.081	0.057	0.068	0.016	0.024	0.045	1.40
64	0.135	0.157	0.151	0.053	0.046	0.043	2.78
66	0.125	0.120	0.114	0.046	0.030	0.028	2.19
67	0.020	0.033	0.028	0.036	0.046	0.044	1.21
69	0.048	0.034	0.025	0.036	0.027	0.043	1.04
71	0.021	0.016	0.009	0.020	0.025	0.012	0.57
72	0.084	0.072	0.094	0.031	0.019	0.022	1.56
73	0.041	0.032	0.018	0.042	0.018	0.031	0.94

77	0.024	0.026	0.039				0.80
79	0.020	0.011	0.022	0.031	0.041	0.052	0.81
81	0.027	0.015	0.005	0.046	0.027	0.033	0.78
102	0.044	0.028	0.019	0.034	0.038	0.026	0.92
129	0.077	0.082	0.084	0.048	0.058	0.036	1.85
159	0.005	0.004	0.011	0.038	0.028	0.023	0.65
173	0.042	0.063	0.058	0.013	0.032	0.018	1.17
						min	0.43
						max	2.99
						mean	1.14

Appendix 10- Analyses with Max Abundance instead of Summed Abundance

Appendix 10. Path analyses assessing the direction and potential causes of effect of agricultural intensity on the maximum recorded abundance of anurans in ponds in the agricultural region of Eastern Ontario. Predictor variables for a given species included nitrate concentration (ni), the best measure of larval habitat quality for that species (% emergent vegetation pond cover (em), water temperature (wt), or pH), and the proportion of landscapes in each of the following: high-intensity row crop cover (hi), adult habitat (either forest (fo) or low-intensity perennial crop cover (lo)) , and wetland cover (we). The scales at which each landscape effect was strongest for each species were 250, 500, or 1000 m and were displayed with each cover type (e.g. for we500, the effects of wetlands were strongest at 500 m). Error terms (residual variance) for abundance and nitrate are denoted by 'e'.

Appendix 11

Appendix 11. Path analysis model fit criteria for Appendix 10: path analyses on effects of agricultural intensity on 'maximum recorded anuran abundance'. Several goodness of fit measures were included to assess the overall fit of each model, with boldness indicating a "good fit". Measures included: the χ^2 "badness of fit" measure (if $p < 0.05$, the model was a bad fit (Hair et al., 2006)), the comparative fit index (if CFI ≥ 0.90 , the model was a good fit (Bentler, 1990)), the Tucker-Lewis index (if TLI > 0.95 , the model was a good fit (Bollen, 1989)), and root mean square error (if RMSEA ≤ 0.07 , the model was a good fit (Hu & Bentler, 1999)).

Species	Model χ^2 , df, p	Model Fit Indices		
		CFI	TLI	RMSEA
<i>A. americanus</i>	6.25, 6, 0.39	0.86	0.50	0.033
<i>H. versicolor</i>	2.59, 6, 0.86	-	-	0
<i>L. catesbeiana</i>	5.39, 6, 0.46	1.0	1.14	0
<i>L. clamitans</i>	4.3, 6, 0.63	-	0.06	0
<i>L. pipiens</i>	3.78, 6, 0.70	1.0	10.96	0
<i>L. sylvatica</i>	11.03, 6, 0.09	0.66	-0.20	0.15
<i>P. crucifer</i>	5.84, 6, 0.44	1.0	1.105	0
<i>P. triseriata</i>	5.82, 6, 0.44	1.0	1.141	0

Appendix 12

Appendix 12. ANOVA output for test of significant differences of nitrate absorbance among ponds, with a random effect of sampling period.

General Linear Model: nitrate absorbance (abs) versus site (site), season (jar)

Method

Factor coding (-1, 0, +1)
Rows unused 18

Factor Information

Factor	Type	Levels	Values
site	Fixed	39	3, 5, 9, 11, 14, 19, 20, 22, 23, 24, 28, 29, 30, 31, 33, 35, 38, 41, 42, 43, 44, 45, 52, 55, 61, 64, 66, 67, 69, 71, 72, 73, 77, 79, 81, 102, 129, 159, 173
jar	Random	2	1, 2

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
site	38	0.099348	0.002614	4.21	0.000
jar	1	0.003336	0.003336	5.37	0.022
Error	176	0.109358	0.000621		
Lack-of-Fit	32	0.097772	0.003055	37.98	0.000
Pure Error	144	0.011585	0.000080		
Total	215	0.211089			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0249269	48.19%	36.71%	24.17%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.03880	0.00175	22.14	0.000	
site					
3	-0.0046	0.0101	-0.46	0.646	1.96
5	-0.0025	0.0101	-0.25	0.807	1.96
9	-0.0103	0.0101	-1.02	0.308	1.96
11	0.0710	0.0101	7.06	0.000	1.96
14	-0.0104	0.0142	-0.73	0.468	2.93
19	-0.0176	0.0101	-1.74	0.083	1.96
20	0.0204	0.0101	2.02	0.045	1.96
22	-0.0238	0.0101	-2.36	0.019	1.96
23	0.0157	0.0101	1.56	0.121	1.96
24	-0.0296	0.0142	-2.08	0.039	2.92
28	-0.0226	0.0101	-2.25	0.026	1.96
29	-0.0091	0.0101	-0.91	0.365	1.96
30	-0.0023	0.0101	-0.23	0.819	1.96
31	0.0147	0.0101	1.46	0.145	1.96
33	-0.0047	0.0142	-0.33	0.742	2.93
35	0.0060	0.0101	0.60	0.550	1.96
38	0.0021	0.0142	0.15	0.883	2.92
41	-0.0086	0.0101	-0.86	0.392	1.96
42	-0.0282	0.0142	-1.98	0.049	2.92
43	0.0079	0.0101	0.78	0.436	1.96
44	0.0137	0.0101	1.36	0.175	1.96
45	-0.0200	0.0101	-1.98	0.049	1.96
52	-0.0096	0.0101	-0.96	0.340	1.96
55	0.0080	0.0101	0.80	0.426	1.96
61	0.0097	0.0101	0.96	0.337	1.96
64	0.0587	0.0101	5.83	0.000	1.96
66	0.0384	0.0101	3.81	0.000	1.96
67	-0.0043	0.0101	-0.43	0.670	1.96
69	-0.0033	0.0101	-0.33	0.743	1.96
71	-0.0216	0.0101	-2.15	0.033	1.96
72	0.0149	0.0101	1.48	0.142	1.96
73	-0.0085	0.0101	-0.84	0.401	1.96
77	-0.0132	0.0142	-0.93	0.353	2.92
79	-0.0093	0.0101	-0.92	0.357	1.96
81	-0.0133	0.0101	-1.32	0.188	1.96
102	-0.0073	0.0101	-0.73	0.469	1.96
129	0.0254	0.0101	2.52	0.013	1.96
159	-0.0206	0.0101	-2.05	0.042	1.96
jar					
1	0.00410	0.00177	2.32	0.022	*

Regression Equation

```

abs = 0.03880 - 0.0046 site_3 - 0.0025 site_5 -
0.0103 site_9 + 0.0710 site_11
      - 0.0104 site_14 - 0.0176 site_19 + 0.0204 site_20 -
0.0238 site_22 + 0.0157 site_23
      - 0.0296 site_24 - 0.0226 site_28 - 0.0091 site_29 -
0.0023 site_30 + 0.0147 site_31
      - 0.0047 site_33 + 0.0060 site_35 + 0.0021 site_38 -
0.0086 site_41 - 0.0282 site_42
      + 0.0079 site_43 + 0.0137 site_44 - 0.0200 site_45 -
0.0096 site_52 + 0.0080 site_55
      + 0.0097 site_61 + 0.0587 site_64 + 0.0384 site_66 -
0.0043 site_67 - 0.0033 site_69
      - 0.0216 site_71 + 0.0149 site_72 - 0.0085 site_73 -
0.0132 site_77 - 0.0093 site_79
      - 0.0133 site_81 - 0.0073 site_102 + 0.0254 site_129
- 0.0206 site_159
      - 0.0011 site_173 + 0.00410 jar_1 - 0.00410 jar_2

```

Equation treats random terms as though they are fixed.

Fits and Diagnostics for Unusual Observations

Obs	abs	Fit	Resid	Std Resid	
4	0.0350	0.1139	-0.0789	-3.48	R
24	0.0040	0.0509	-0.0469	-2.07	R
43	0.0370	0.1139	-0.0769	-3.39	R
63	0.0030	0.0509	-0.0479	-2.11	R
65	0.1570	0.1016	0.0554	2.44	R
82	0.0490	0.1139	-0.0649	-2.86	R
104	0.1510	0.1016	0.0494	2.18	R
121	0.1800	0.1057	0.0743	3.27	R
160	0.1780	0.1057	0.0723	3.19	R
180	0.1050	0.0427	0.0623	2.74	R
182	0.0460	0.0934	-0.0474	-2.09	R
199	0.1800	0.1057	0.0743	3.27	R
221	0.0430	0.0934	-0.0504	-2.22	R

R Large residual

Expected Mean Squares, using Adjusted SS

	Source	Expected Mean Square for Each Term
1	site	(3) + Q[1]
2	jar	(3) + 99.0000 (2)

3 Error (3)

Error Terms for Tests, using Adjusted SS

	Source	Error DF	Error MS	Synthesis of Error MS
1	site	176.00	0.0006	(3)
2	jar	176.00	0.0006	(3)

Variance Components, using Adjusted SS

Source	Variance	% of Total	StDev	% of Total
jar	0.0000274	4.23%	0.0052363	20.56%
Error	0.0006213	95.77%	0.0249269	97.86%
Total	0.0006488		0.0254709	