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# Landscape features associated with lyme disease risk in a suburban residential environment

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## Abstract

The landscape features of residential properties within two communities were studied in relation to the abundance of the tick vector *Ixodes scapularis*. Habitat types of 400 properties, located in a Lyme disease endemic area of Westchester Co., New York, USA, were categorized into lawn, ornamental, ecotone, woods, and stone wall as measured from aerial photographs and sampled for nymphal-stage ticks. Logistic regression results indicate that presence or absence of ticks is influenced by the proportion of either lawn or woodland, and total woodland area. Poisson regression results indicate the abundance of nymphs is negatively associated with proportion, area, and patch frequency of lawn, and positively associated with proportion, area, and patch frequency of woodland. Predictions of tick presence and abundance from landscape features at the scale of individual property is useful for implementing disease prevention measures.

## Introduction

Arthropod-borne zoonotic diseases have long been known to have intricate links with landscape features (Pavlovsky 1966). Studies on landscape epidemiology of infectious diseases, although frequently published in the Russian literature, have been rare in the US. Consequently, our understanding of arthropod-borne infectious disease epidemiology in the US, in general, has not benefited from an approach based upon landscape ecology. Lyme disease is the most common arthropod-borne infectious disease affecting humans in the United States (CDC 1991). New York state reports more human cases of Lyme disease than any other state because two densely-populated southern counties, Westchester and Suffolk, have a high residential risk of infection (Falco and Fish 1988; Fish et al. 1992). Attributes of the suburban residential landscape in Westchester Co. have been shown to influence risk of human infection (Maupin et al. 1991). This feature of Lyme disease provides an important opportunity for further investigations on the landscape epidemiology of a major vector-borne disease in the US.

Lyme disease is caused by infection of the spirochete *Borrelia burgdorferi* which is transmitted by the tick vector, *Ixodes scapularis* (= *Ixodes dammini*, Oliver et al. 1993) in the northeastern US. In this region, *I. scapularis* exhibits a two year life cycle with overlapping cohorts (Fish 1993). Larvae acquire infection while feeding on small mammals and birds, many of which are reservoirs for *B. burgdorferi* infection (Donohue et al. 1987; Magnarelli et al. 1988; Fish and Daniels 1990; Battaly and Fish 1993). After molting to the nymphal stage, over-wintering ticks transmit *B. burgdorferi* the following summer while feeding as nymphs. Infected nymphs feeding upon reservoir-competent hosts in June and July, just prior to the onset of larval feeding activity of the next generation in August, perpetuate the enzootic cycle of *B. burgdorferi* transmission. Infected nymphs also are responsible for most human cases of Lyme disease, because in the highly endemic areas of the Northeast, *I. scapularis* nymphs also feed upon humans (Fish 1993). In this region, the prevalence of *B. burgdorferi* in nymphal *I. scapularis* collected from residential properties can range 14- 29% (Maupin et al. 1991; Stafford and Magnarelli 1993).

Adult *I. scapularis* molt from nymphs and begin to seek a host during the fall. Mating most often occurs on a host and females require a large blood meal to reproduce. Large mammals, particularly deer, appear to be preferred hosts for this stage, and there are data to suggest that *I. scapularis* populations correlate with those of white-tailed deer (*Odocoileus virginianus*) (Wilson, et al. 1985, 1990; Duffy et al. 1994).

Although evidence suggests that *B. burgdorferi*-infected ticks have existed on Long Island, NY since at least the 1940s (Persing et al. 1990), their recent spread throughout the northeastern and mid-Atlantic states is linked to reforestation and the explosive growth of populations of white-tailed deer (Spielman et al. 1985; Barbour and Fish 1993). Although the amount of forest has not changed significantly in recent decades, the spatial structure has changed from large contiguous forest to fragmented patches disrupted by suburban residential development. This present landscape can be broadly characterized as a mosaic of man-made structures and ornamental vegetation (e.g. lawns, gardens, and hedge rows) within a matrix of natural woodland. The abundant patches, corridors and peninsulas of natural woodland adjacent to ornamental vegetation provide not only the resources necessary to support large numbers of many reservoir-host species and deer, but the spatial structure conducive to their dispersal (Merriam and Lanoue 1990; Sillings 1982). It is here, in suburban residential areas, where the combination of high human population densities, uncontrolled deer populations, and a wide array of reservoir hosts for the immature stages of *I. scapularis*, results in an extremely high risk of human exposure to *B. burgdorferi* (Falco and Fish 1988; Dennis 1991; Maupin et al. 1991; Lastavica 1992). In order to better understand the spatial aspects of Lyme disease risk, we have quantitatively investigated the abundance of nymphal *I. scapularis* in relation to landscape features for two Lyme disease endemic residential communities in Westchester County, New York.

## Methods

### *Study area*

Two Lyme disease endemic residential communities located in central Westchester County, New York, approximately 56 km north of New York City, were chosen as study areas. The approximately 6 km$^2$ study area in the village of Chappaqua, Town of New Castle, is located 10 km from the second study area of 2.3 km$^2$ in the village of Armonk, Town of North Castle. The towns are contiguous and both study areas have an elevation range of 60-155 meters. Central Westchester County consists of small urban centers surrounded by suburban residential properties within re-forested land of predominantly oak (*Quercus* spp.) and hickory (*Carya ovata*) with maple (*Acer saccharum*), tulip (*Liriodendron tulipifera*), and black walnut (*Juglans nigra*) (Kingsley 1985). The age of second growth woodland ranges from recent to approximately 80 years old (Shoumatoff 1979). Species composition of wildlife is similar in the two communities and includes several common species known to host *I. scapularis*: white-footed mice (*Peromyscus leucopus*), gray squirrels (*Sciurius carolinensis*), red squirrels (*Tamiasciurus hudsonicus*), chipmunks (*Tamias striatus*), opossum (*Didelphis virginiana*), raccoon (*Procyon lotor*), striped skunk (*Mephitis mephitis*), white-tailed deer (*Odocoileus virginianus*) (Fish and Dowler 1989; Fish and Daniels 1990), and some common bird species (Battaly and Fish 1993).

### *Sampling methods*

The sampling unit in this study was the individually owned residential property. All property owners within each study area were solicited for participation by mail and telephone and positive respondents were included in the study. We chose this sampling unit for two reasons. Firstly, because exposure to infected ticks is known to be high in the suburban residential environment (Falco and Fish 1988), and assuming that most residents spend the majority of their time within their own property borders, the individual property is the logical sampling unit for addressing hypotheses relating to risk of Lyme disease. Secondly, because each property is largely the product of and under the control of each homeowner, it represents a unique independent configuration of a relatively small set of discrete habitat types.

Four hundred residential properties (118 in Armonk, 282 in Chappaqua) were sampled for nymphal *I. scapularis* from June 5–August 15, 1990 using drag cloths. A one square meter piece of double thickness white corduroy cloth was dragged over habitat substrate and vegetation to collect host-seeking ticks (Falco and Fish 1992). The cloth was examined every 20 meters, and attached ticks were removed, counted, and placed in vials. The landscape was broadly characterized into five types: Lawn (maintained domestic grasses), ornamental plantings (ground cover, flower gardens, shrubs and small trees), ecotone (unmaintained areas that contain components of two or more habitat types), woodland (closed-canopy deciduous forest with leaf litter), and stone wall. All representative habitats on each property were sampled. The sampling effort was based on drag-sample data from a previous study (Maupin et al. 1991) and reflects the relative abundance of ticks expected in each habitat. The total sampling effort for each property was 300 $m^2$ of lawn, 150 $m^2$ of ornamentals, 100 $m^2$ of ecotone, and 50 $m^2$ of woodland. In addition we sampled 10 $m^2$ of stone wall on each property, where present (Table 1). Man-made stone walls are used frequently as refugia by small mammals (Sinclair et al. 1967; Barry and Francq 1980; Frank et al. 1992) and the presence of nymphal ticks upon them was observed in a previous study (G. Maupin and E. Campos, pers comm). The total number of meters sampled/habitat type and the total number of nymphs collected in each of five habitat types was recorded for each property. The sampling effort (total meters sampled/property) was approximately equal between Armonk ($\bar{x}$ = 442 meters) and Chappaqua ($\bar{x}$ = 418 meters).

Nymphal *I. scapularis* exhibit a strong seasonal pattern of abundance in the northeastern US. Nymphs begin to appear in the spring , increasing in abundance until a peak is reached in early June, after which the numbers begin to decline. Because of this seasonality, tick numbers/habitat/property were adjusted according to the date of sample based on population data from permanent study plots (Fish 1993) (Figure 1). The number of ticks collected/habitat type/property was multiplied by a scaling factor that would adjust those numbers to reflect maximum abundance if collections were conducted at the time of peak population. Tick abundance data were adjusted prior to all subsequent analyses.

*Table 1.* Landscape comparisons between two Westchester communities (1990 data). All variables are represented as the mean per property (+/- standard error). The Student's T-test was used for comparing variable values between communities. Proportion (%) variables were transformed with the arcsin square root transformation prior to testing. Probabilities $> 0.05$ are not statistically significant.

| | Chappaqua N = 256 | Armonk N = 111 | Probability |
|---|---|---|---|
| Lawn area $m^2$ | 616.5 (75.7) | 935.2 (81.6) | 0.013 |
| Lawn patches # | 1.76 (.045) | 1.92 (.064) | 0.046 |
| Lawn% | 17.8 (.9) | 32.9 (2.2) | $< 0.0001$ |
| Ornamental area $m^2$ | 235.8 (17.5) | 178.4 (17.5) | 0.048 |
| Ornamental patches # | 2.42 (.09) | 2.31 (.11) | 0.444, ns |
| Ornamentals% | 7.42 (.47) | 6.64 (.70) | 0.449, ns |
| Ecotone area $m^2$ | 257.5 (22.9) | 404.6 (52.2) | 0.003 |
| Ecotone patches # | 0.88 (.043) | 1.21 (.065) | 0.0001 |
| Ecotone% | 8.81 (.77) | 11.54 (1.28) | 0.003 |
| Woodland area $m^2$ | 2810.8 (161.0) | 2135.8 (193.3) | 0.015 |
| Woodland patches # | 1.27 (.038) | 1.01 (.055) | 0.0002 |
| Woodland% | 65.6 (1.5) | 48.5 (2.9) | $< 0.0001$ |

### *Vegetative cover-type analytic methods*

Vegetative cover on 367 residential properties (256 Chappaqua, 111 Armonk) was interpreted stereoscopically from aerial photographs (1: 2400) taken in March 1990. An enlarged image of each property was captured and imported into a PC-386 using a video image analysis system (JAVA, Jandel Scientific, Inc.) in order to digitize vegetative cover. Areas delineating distinct patches of the four vegetative habitat types (described above) were measured and recorded for each property into a database for statistical analysis. Stone walls could not be measured accurately by this method, as determined by ground surveys of a sub-sample of properties, and were therefore recorded as "present" or "absent" on the property.

### *Statistical methods*

Habitat variables such as patch size and frequency among vegetative cover types were normally distributed, therefore comparisons between the two study areas were conducted with traditional parametric statistical methods.

Because tick abundance data were significantly

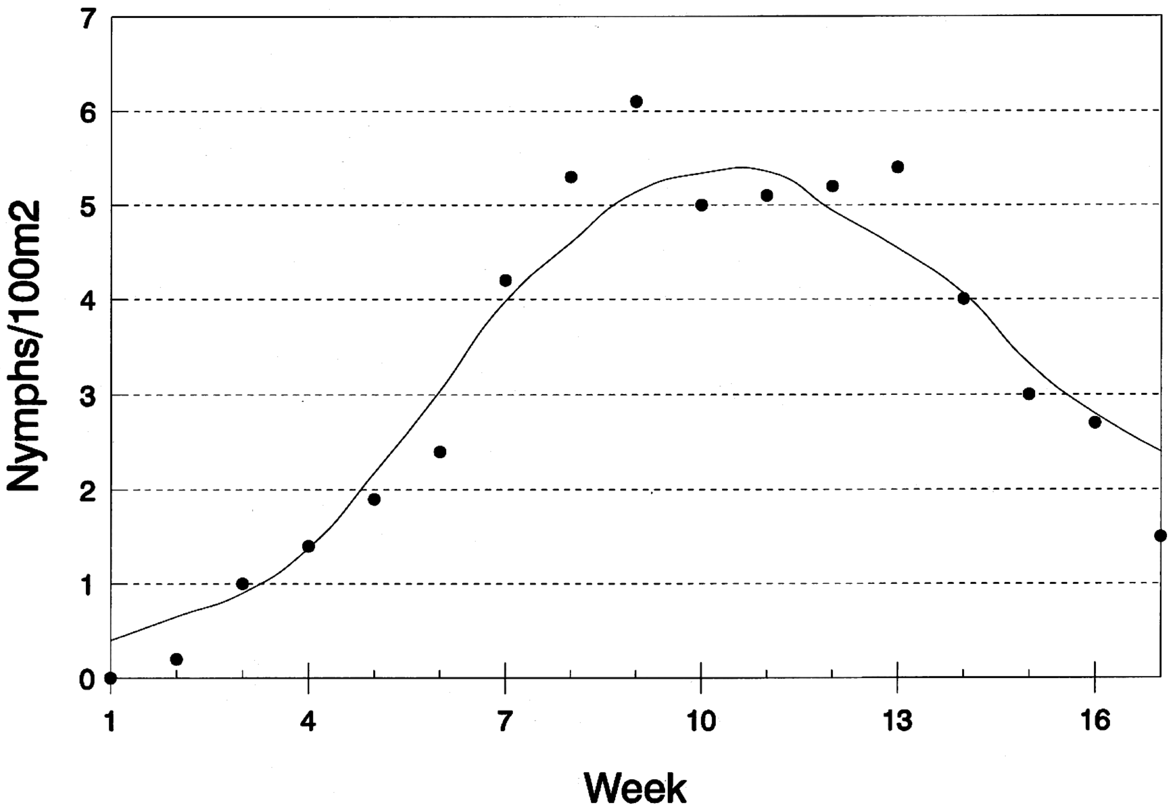

*Figure 1.* Seasonal abundance of nymphal *I. scapularis* in Weschester Co. NY from April 26-August 13, 1990.

skewed with many zero values, and the mean and variance were approximately equal, we employed a Poisson regression (McCullagh and Nelder 1983; Jongman et al. 1987). As a comparison, the data were dichotomized as presence or absence in a logistic regression approach. The dependent variables used in the univariate Poisson regression models included the abundance of nymphs collected in each habitat type per property or abundance numbers divided by total vegetative cover/property (a density measure). Purported independent variables explored in univariate relationships with Poisson or dichotomous dependent variables were proportion of total area, absolute area and frequency of patches of lawn, ornamental plants, ecotone and woodland. For example, three variables were explored for woodland: woodland as a proportion of total area/property, total woodland area/property and number of patches of woodland/property. Stone walls were characterized as present or absent.

## Results

The total area of vegetative cover per property did not differ between Chappaqua (N = 256, $\bar{x}$ = 0.392 ha, sd = ± 0.74) and Armonk (N = 111, $\bar{x}$ = 0.365 ha, sd = ± 0.57) (T-test = 0.819, df = 365, p = 0.41). Similarly, the habitat types comprising the properties were not statistically different between the two study areas. Similar proportions of the properties in Armonk and Chappaqua had lawn and ornamental vegetation, but Chappaqua was slightly greater in proportion of properties found to have ecotone and woodland vegetation (Figure 2). The mean areas, proportions, and patch frequencies of these habitat types often varied significantly between the two communities. In general the most notable differences were in lawn and woodland habitats. The property profile in Chappaqua was one of fewer patches of lawn, less total lawn area and low proportion of lawn relative to the total vegetation,

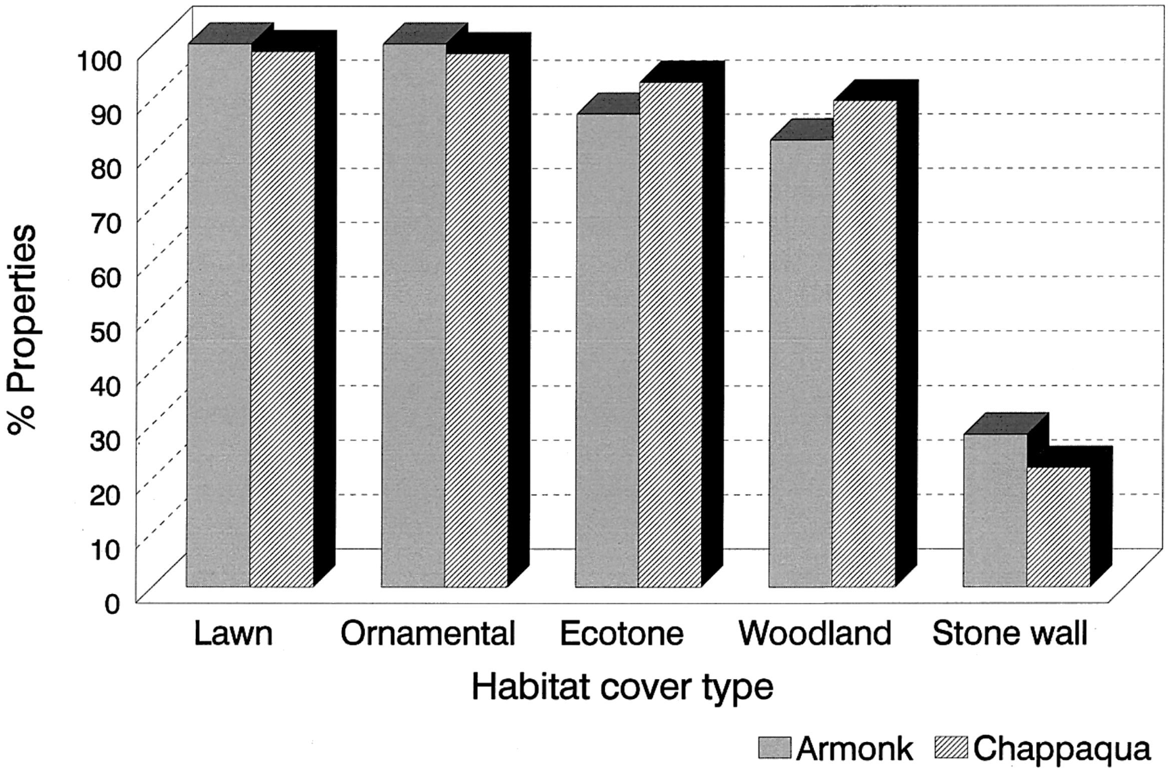

*Figure 2.* Percent of residential properties in two communities having each habitat type.

while in Armonk properties had a significantly greater number of lawn patches, that covered more area and represented a greater proportion of total vegetation. Woodland habitat measures showed the opposite trend between the two communities (Table 1). Ecotone habitat measures also differed significantly between the two study areas, with properties in Armonk having a slightly greater mean area, number of patches, and proportion of ecotone.

*I. scapularis* nymphs were collected from 89% of the properties in Chappaqua and from 52% of the properties in Armonk. Mean nymphal abundance per property was significantly different between the two study areas with Chappaqua having roughly four times the mean number of nymphs collected ($\overline{x} = 7.58$, SE $= \pm 0.63$) than Armonk ($\overline{x} = 1.61$, SE $= \pm 0.34$) ($p < 0.0001$). Nymphal density/100 meters showed a similar trend with densities five times greater in Chappaqua ($\overline{x} = 2.0$, SE $= \pm 0.18$) than in Armonk ($\overline{x} = 0.4$, SE $= \pm 0.10$) ($p < 0.001$).

*I. scapularis* were collected in all vegetative habitat types, however, most of the nymphs were collected from woodland while fewer numbers of ticks were collected in ecotone, ornamentals and lawn . This pattern was similar for both communities and corroborates data collected in Armonk in 1989 (Maupin, et al. 1991). Questing nymphs were also collected from stone walls in both communities, and at a surprisingly high density in Chappaqua (Figure 3).

Given the general similarity between habitat composition and patterns of nymphal occurrence among the habitat types, the data from both communities were combined for logistic and Poisson regression analyses to determine the predictive value of general, broad landscape characterizations associated with nymphs in the suburban environment. The logistic regression model using a dichotomous dependent variable (presence or absence of ticks on a property) indicates that the presence (or absence) of ticks on a specific property is significantly influenced in univariate models by proportions of lawn (parameter estimate = –2.6469, p = 0.001) and woodland (parameter estimate = 1.53150, p = 0.002), and by total woodland area (parameter estimate = –0.0014, p = 0.0145). The presence of nymphal ticks on a residential property is negatively influenced by the proportion of lawn rel-

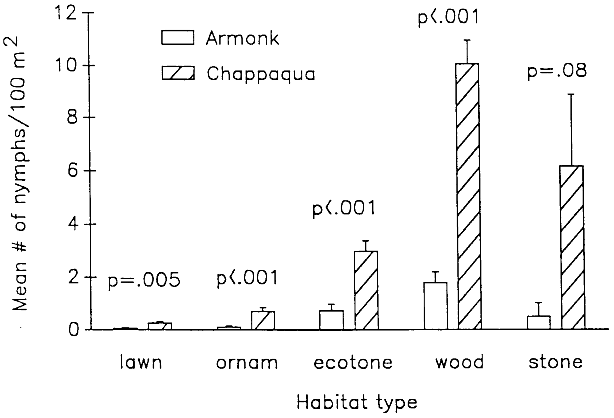

*Figure 3.* Mean (+/- standard error) densities of nymphal *I. scapularis* in five habitats in two suburban residential communities. Statistical p values are the result of paired Student's t-tests on log transformed data.

ative to total vegetation and positively influenced by proportion of woodland. In this model there is also a slight negative effect of woodland area on the presence of nymphs.

The Poisson regression model using abundance of nymphs/habitat/property as the dependent variable suggests that increase in the proportion, area, and frequency of lawn negatively influences tick numbers while increase in the proportion, area and frequency of woodland would predict increase in numbers of ticks/property. In this model the measures of ecotone do not yield a consistent influence on tick abundance, and only one measure of ornamental habitat (proportion of total vegetation) suggests a relationship (Table 2). All other univariate relationships were not significant, ie. the 95% asymptotic confidence interval included zero. Employing nymphal densities (ticks/meter) as the dependent variable yielded no significant relationships with any of the independent variables in this model.

The univariate Poisson regression models using log transformed nymphal abundance and log transformed nymphal densities as the dependent variables produced similar results suggesting predictive relationships between the proportions of lawn (parameter estimate for abundance = –1.1644, $p < 0.01$, density = –1.115, $p < 0.01$) and woodland (parameter estimate for abundance = 0.6625, $p < 0.01$, density = 0.6097, $p < 0.01$) and ticks. The total woodland area per property, while significant in both models (parameter estimate for abundance = 0.04, $p < 0.01$, density = –0.036, $p < 0.01$) , appears to be a weak predictor based on the instability of the parameter estimate. All other independent variables were not significant in univariate relationships with the dependent variable. Interactions were explored among the significant independent variables but yielded no clarifying results. In addition, we examined the relationships among the independent regressor variables. Marginally significant relationships were observed but did not clarify the modeling process. The proportions of lawn and woodland, and total area of woodland per property remained significant under all three scales of measurement, however, the transformations make it difficult to compare and yield a single simple model.

*Table 2.* Univariate Poisson regression model using abundance of nymphal ticks/property.

| Variable | Parameter estimate | Standard error |
|---|---|---|
| Ecotone proportion | –0.5568* | 0.1857 |
| Lawn proportion | –2.5089** | 0.1590 |
| Ornamental proportion | –4.0728** | 0.3830 |
| Woodland proportion | 1.5041** | 0.0969 |
| Lawn area | –0.1192** | 0.0316 |
| Ecotone area | 0.1573** | 0.0440 |
| Woodland area | 0.0840** | 0.0070 |
| Woodland frequency | 0.3632** | 0.0302 |
| Lawn frequency | –0.1532** | 0.0313 |

* = $p < 0.01$, ** = $p < 0.001$

The untransformed variables, proportion of ecotone, area of ecotone, and proportion of ornamental vegetation, appear significant in the univariate Poisson regression models for abundance data. When transformed on a logarithmic scale, the resulting Poisson regression parameters are no longer significant. The three transformed (logarithmic) variables are significant in models where nymphal density is modeled.

In summary, the proportion of lawn is the strongest determinant in our models and is inversely related to nymphal abundance on residential properties (Figure 4). The proportion of deciduous woodland, also a significant determinant, is positively related to tick abundance (Figure 5). Woodland area, while a significant determinant among the logistic and Poisson models tested here, is unstable, and not useful in the context of our sampling unit, the residential property.

## Discussion

In the suburban landscape examined here, habitat structure significantly influences relative nymphal abundance at the scale of the residential property. Significantly fewer nymphal ticks were found on properties where the proportion of lawn was high relative to the proportion of natural woodland. The general pattern of nymphal distribution among habitat types found here is similar to that previously reported for other communities in the Northeast (Maupin et al. 1991; Ginsberg and Ewing 1989; Stafford and Magnarelli 1993). At a spatial scale similar to this study, Adler et al. (1992) report greater larval and nymphal *I. scapularis* on mice (*P. leucopus*) in woody habitats and lower numbers in grassy habitats on a non-residential northeastern island. On a regional scale, using advanced remote sensing and GIS techniques, tick infested deer were associated with deciduous woodland and sandy soil along river courses (Kitron et al. 1991), while epidemiological data show a strong correlation of human Lyme disease cases with residence in deciduous woodland and in close proximity to watershed areas (Glass et al. 1992).

Taken together, the data strongly suggest that the reforested landscape, which now characterizes numerous suburban communities along the east coast, is the major underlying factor contributing to high populations of *I. scapularis* and consequential high incidence of Lyme disease in this region. Woodland habitat is the primary refugia for small and medium-sized mammals and birds which host immature *I scapularis*, as well as deer, which are the reproductive host for adult ticks. There is convincing evidence that deer are critical in the establishment and maintenance of *I. scapularis* populations (Wilson et al. 1985). Today, with the regrowth of the forests, the extirpation of natural predators, and severe restrictions on hunting, deer populations are as high or higher than during any previous time. Also, the lack of hunting pressure in suburban areas over many generations has resulted in deer which are less wary of humans and often forage and bed on residential properties (Fish, Frank, Daniels, and Fargione, unpublished data).

In addition to deer, a small mammal population capable of maintaining *B. burgdorferi* infection is a crucial factor contributing to the zoonotic maintenance of Lyme disease in the eastern US. *P. leucopus* populations have been shown to increase with habitat fragmentation (Robinson et al. 1992). The fragmentation of continuous woodland creates edge habitat which often is more structurally complex and species rich, in turn providing additional resources which are attractive not only to mice, but also to a wide array of vertebrate species including deer (Coblentz 1970; McCaffery et al. 1974), chipmunks, and raccoons, all known to serve as hosts for immature *I. scapularis*.

The significant differences in nymphal densities on residential properties between the two communities is only partly explained in our models by the relative proportions of lawn and woodland. Other variables, not examined here, would most likely enhance the predictive value our models. For example, quantifying the components of the matrix surrounding each property and relating them spatially to the vegetation comprising the property would refine and increase the predictive power of subsequent models. The instability of our “woodland area” variable was likely due to the absence of such information. For example, a patch of woodland on one property surrounded by lawn or pavement beyond its borders would be ecologically very different from another property where a woodland patch of the same area was surrounded by contiguous woodland. Proximity to unfragmented woodland (eg. nature preserves, watersheds) and the geometry of forested corridors may also be important.

The abundance of nymphs collected from manmade stone walls was surprising. These walls, occurring in all habitat types but most often in woodland, are remnants of the agricultural landscape over a century ago that remain a significant feature of the suburban landscape (Allport 1990). The lack of statistical significance of nymphal abundance due to presence or absence of stone wall on the property may be due to insufficient sampling effort (10 meters/property) or our inability to remotely quantify this habitat. On the other hand, host density may not be significantly affected by this habitat type (Sinclair et al. 1967), therefore, stone wall presence may be predictive of the spatial distribution of nymphal ticks, but a poor predictor of overall nymphal tick density. Further work is needed to elucidate the specific relationship between stone walls and tick abundance.

The data presented here are unique in showing the predictive value of certain habitat measures at the small scale of the residential property. Prediction at this scale is useful for the implementation of disease prevention measures (Curran *et al*. 1993). Improved prediction may be achieved with more information on the behavioral ecology of reservoir hosts in relation to the suburban landscape. For example, movement patterns of white-footed mice vary depending on

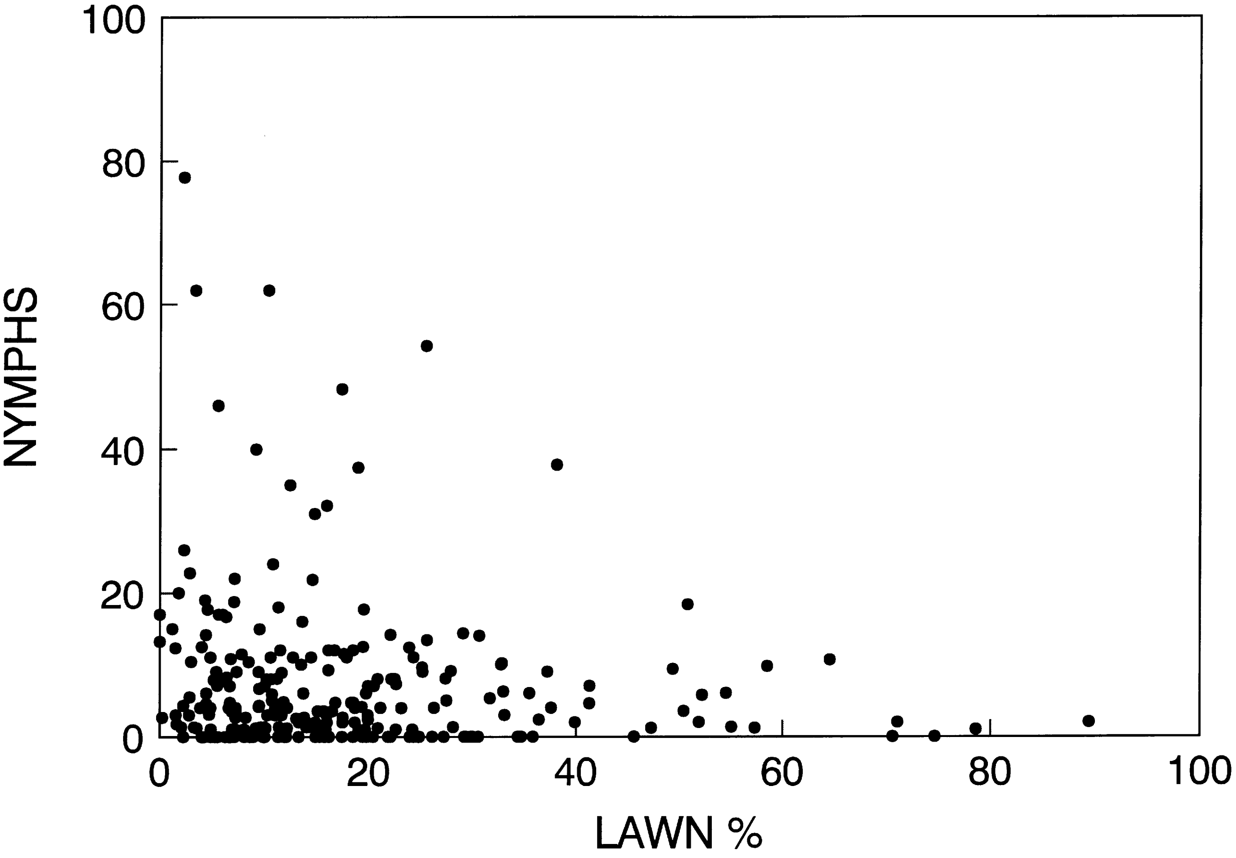

*Figure 4.* Abundance of nymphal *I. scapularis* on suburban properties as a function of the proportion of lawn habitat on the property.

the habitat (Barry and Francq 1990) and their refugia in residential areas are often different than those in unfragmented deciduous woodland. Their behavioral ecology will likely affect the density and distribution of ticks around residential structures (Frank and Daniels unpub. data). Subsequent models would benefit from a more regional, geographical approach to landscape analysis integrated with information regarding the relationships among habitat types and the various host populations.

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## References

Adler, G.H., S.R. Telford III, M.L. Wilson and A. Spielman, 1992. Vegetation structure influences the burden of immature *Ixodes dammini* on its main host, *Peromyscus leucopus*. Parisitology 105: 105–110.

Allport, S. 1990. Sermons in stone: the stone walls of New England and New York. W.W. Norton and Company, Inc., New York.

Barbour, A.G. and D. Fish, 1993. The biological and social phenomenon of Lyme disease. Science 260: 1610–1616.

Barry, R.E. and E.N. Francq, 1980. Orientation to landmarks within the preferred habitat by *Peromyscus leucopus*. Journal of Mammalogy 61: 292–303.

Battaly, G.R. and D. Fish, 1993. Relative importance of bird species as hosts for immature *Ixodes dammini* (Acari: Ixodidae) in a suburban residential landscape of southern New York State. Journal of Medical Entomology 30: 740–747.

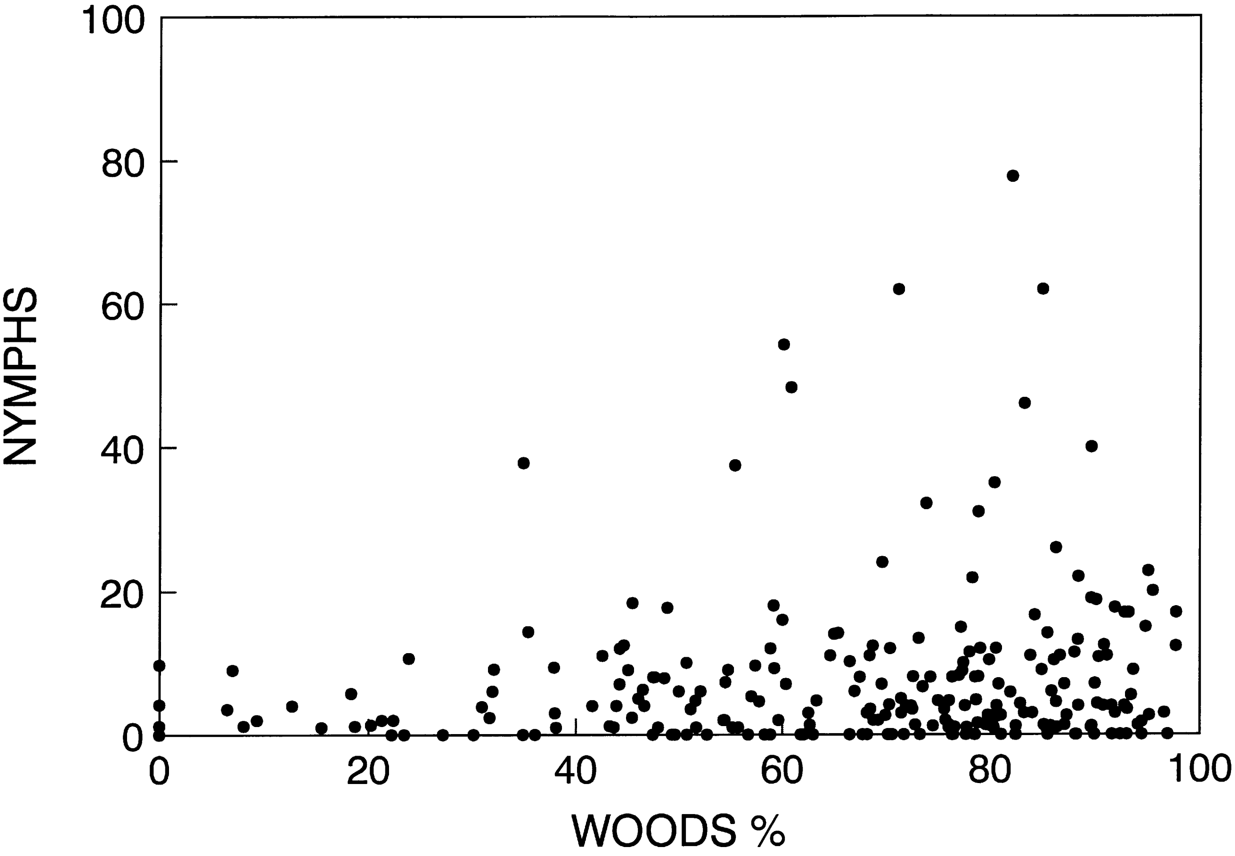

*Figure 5.* Abundance of nymphal *I. scapularis* on suburban properties as a function of the proportion of woodland habitat on the property.

Centers for Disease Control. 1991. Lyme disease surveillance-United States, 1989–1990. Morbidity and Mortality Weekly Report 40: 417–421.

Coblentz, B.E. 1970. Food habits of George Reserve deer. Journal of Wildlife Management 34: 535–540.

Curran, K.L., Fish, D. and Piesman, J. 1993. Reduction of nymphal *Ixodes dammini* (Acari: Ixodidae) in a residential suburban landscape by area application of insecticides. Journal of Medical Entomology 30: 107–113.

Dennis, D.T. 1991. Lyme disease-tracking an epidemic. Journal of the American Medical Association 266: 1269–1270.

Donohue, J.G., J. Piesman and A. Speilman, 1986. Reservoir competence of white-footed mice for Lyme disease spirochetes. American Journal of Tropical Medicine and Hygiene 36: 94–98.

Duffy, D.C., S.R. Campbell, D. Clark, C. DiMotta and S. Gurney, 1994. *Ixodes scapularis* (Acari: Ixodidae) deer tick mesoscale populations in natural areas: Effects of deer, area, and location. Journal of Medical Entomology 31: 152–158.

Falco, R.C. and D. Fish, 1988. Prevalence of *Ixodes scapularis* near the homes of Lyme disease patients in Westchester County, New York. American Journal of Epidemiology 127: 826–830.

Falco, R.C. and D. Fish, 1992. a comparison of methods for sampling the deer tick, *Ixodes dammini* in a Lyme disease endemic area. Experimental and Applied Acarology 14: 165–173.

Fish, D. 1993. Population ecology of *Ixodes dammini* In: Ecology and Environmental Management of Lyme Disease (Edited by H.S. Ginsberg), 25–42. Rutgers University Press, New Brunswick, NJ.

Fish, D. and T.J. Daniels, 1990. The role of medium-sized mammals as reservoirs of *Borrelia burgdorferi* in southern New York. Journal of Wildlife Diseases 26: 339–345.

Fish, D., T.J. Daniels, D.H. Frank and R.C. Falco, 1992. Ecology of Lyme disease in the suburban residential landscape of southern New York state. In: Proceedings First International Conference on Tick-Borne Pathogens at the Host Vector Interface (Edited by U.G. Munderloh and T.J. Kurtti), 274–281. University of Minnesota College of Agriculture, Department of Entomology and Minnesota Extension Service, St. Paul, MN.

Fish, D. and R.C. Dowler, 1989. Host associations of ticks (Acari: Ixodidae) parasitizing medium-sized mammals in a Lyme disease endemic area of southern New York. Journal of Medical Entomology 26: 200–209.

Glass, G.E., J.M. Morgan III, D.T. Johnson, P.M. Noy, E. Israel and B. Schwartz, 1992. Infectious disease epidemiology and GIS: A case study of Lyme disease. Geo Info Systems Nov./Dec.: 65–69.

Ginsburg, H.S. and C.P. Ewing, 1989. Habitat distribution of *Ixodes dammini* (Acari: Ixodidae) and Lyme disease spirochetes on Fire Island, New York. Journal of Medical Entomology 26: 183–189.

Jongman, R.H.G., C.J.F. ter Braak and O.F.R. van Tongeren, 1987. Data analysis in community and landscape ecology. Pudoc, Wageningen, Holland.

Kingsley, N.P. 1985. A forester's atlas of the Northeast. General Technical Report NE–95, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Broomall, Pa.

Kitron, U., J.K. Bouseman and C.J. Jones, 1991. Use of the ARC/INFO GIS to study the distribution of Lyme disease ticks in an Illinois county. Preventive Veterinary Medicine 11: 243–248.

Lastavica, C.C. 1992. Deer, ticks, and Lyme disease. New York State Journal of Medicine 92: 2–4.

Lees, A.D. 1943. Water balance in *Ixodes ricinus* and certain other species of ticks. Parisitology 37: 1–20.

Magnarelli, L.A., J. Anderson, K. Hyland, D. Fish and J. McAninch, 1988. Serologic analyses of *Peromyscus leucopus*, a rodent reservoir of *Borrelia burgdorferi*, in northeastern United States. Journal of Clinical Microbiology 26: 1138–1141.

Maupin, G.O., D. Fish, J. Zultowsky, E.G. Campos and J. Piesman, 1991. Landscape ecology of Lyme disease in a residential area of Westchester County, New York. American Journal of Epidemiology 133: 1105–1113.

McCaffery, K.R., J. Tranetzki and J. Piechura Jr. 1974. Summer foods of deer in northern Wisconsin. Journal of Wildlife Management 38: 215–219.

McCullagh, P. and J.A. Nelder, 1983. Generalized linear models. Chapman and Hall, London, England.

Merriam, G. and A. Lanoue, 1990. Corridor use by small mammals: field measurement for three experimental types of *Peromyscus leucopus*. Landscape Ecology 4: 123–131.

Oliver, J.H. Jr., M.R. Owsley, H.J. Hutcheson, A.M. James, C. Chen, W.S. Irby, E.M. Dotson and D.K. McLain, 1993. Conspecificity of the ticks *Ixodes scapularis* and *I. dammini* (Acari: Ixodidae). Journal of Medical Entomology 30: 54–63.

Pavlovsky, E.N. 1966. Natural nidality of transmissible diseases, with special reference to the landscape epidemiology of zooanthroponses. N.D. Levine (editor). University of Illinois Press, Urbana and London.

Persing, D.H., S.R. Telford III, P.N. Rys, D.E. Dodge, T.J. White, S.E. Malawista and A. Spielman, 1990. Detection of *Borrelia burgdorferi* DNA in museum specimens of *Ixodes dammini* ticks. Science 249: 1420–1423.

Robinson, G.R., R.D. Holt, M.S. Gaines, S.P. Hamburg, M.L. Johnson, H.S. Fitch and E.A. Martinko, 1992. Diverse and contrasting effects of habitat fragmentation. Science 257: 524–526.

Shoumatoff, A. 1979. Westchester, Portrait of a County. Random House, Inc., New York.

Sillings, J. 1982. White-tailed deer studies in a suburban community: Ground counts, impacts on natural vegetation and electric fencing to control browsing. University of Minnesota Thesis, Minneapolis.

Sinclair, N.R., L.L. Getz and F.S. Bock, 1967. Influence of stone walls on local distribution of small mammals. University of Connecticut Occasional Papers of the Biological Science Service 1: 43–62.

Spielman, A., M.C. Wilson, J.F. Levine and J. Piesman, 1985. Ecology of *Ixodes dammini*-borne human babesiosis and Lyme disease. Annual Review of Entomology 30: 439–460.

Stafford, K.C. III and L.A. Magnarelli, 1993. Spatial and temporal patterns of *Ixodes scapularis* (Acari: Ixodidae) in southeastern Connecticut. Journal of Medical Entomology 30: 762–771.

Wilson, M.L., G.H. Adler and A. Spielman, 1985. Correlation between deer abundance and that of the deer tick *Ixodes dammini* (Acari: Ixodidae). Annals of the Entomological Society of America 78: 172–176.