# Roads and Landscape Pattern in Northern Wisconsin Based on a Comparison of Four Road Data Sources

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**Abstract:** *Roads are important components of landscapes; they fragment habitat, facilitate invasive species spread, alter hydrology, and influence patterns of land use. Previous research on the ecological impacts of roads may have underestimated their effect because currently available sources of road data do not include the full road network. We compared differences in road density and landscape pattern among U.S. Census Bureau TIGER line files, U.S. Geological Survey 1:100,000-scale digital line graphs, and U.S. Geological Survey 1:24,000-scale digital raster graphics in northern Wisconsin to road data derived from 1:40,000-scale digital orthophotos. Road density measured from digital orthophotos (2.82 km/km$^2$) was significantly greater than that of digital raster graphics (1.62 km/km$^2$) and more than double that of digital line graphs (1.21 km/km$^2$) and TIGER (1.27 km/km$^2$) data. The increased road densities in raster graphics and orthophoto data were mainly due to the addition of minor roads. When all roads were used to define patch boundaries, landscape metrics produced with orthophoto data showed significantly greater levels of fragmentation than those based on line or raster graphics. For example, maximum patch size was 1074 ha and total edge was 109 km for line graphs, compared with 686 ha and 211 km for orthophoto data. Roads are missing in commonly used data, primarily because mapping standards systematically exclude minor roads. These standards are not ecologically based and may result in false assumptions about the ecological effects of roads. We recommend that future studies take special consideration of the completeness of road data and consider whether all ecologically relevant roads are included.*

**Key Words:** digital line graph, digital orthophoto, digital raster graphic, fragmentation, habitat models, landscape pattern, road density, road ecology

Caminos y Patrón del Paisaje en el Norte de Wisconsin con Base en una Comparación de Cuatro Fuentes de Datos de Caminos

**Resumen:** *Los caminos son componentes importantes del paisaje; fragmentan hábitat, facilitan la dispersión de especies invasoras, alteran la hidrología e influyen en los patrones de uso de suelo. Investigaciones previas de los impactos ecológicos de caminos han subestimado su efecto porque las fuentes de datos sobre caminos disponibles actualmente no incluyen la red completa de caminos. Comparamos las diferencias en la densidad de caminos y el patrón del paisaje de archivos lineales de U.S. Census Bureau TIGER, gráficos lineales digitales de U.S. Geological Survey escala 1:100,000 y gráficos ráster digitales de U.S. Geological Survey escala 1:24,000 en el norte de Wisconsin con datos derivados de ortofotos digitales escala 1; 40,000. La densidad de caminos medida en ortofotos digitales (2.82 km/km$^2$) fue significativamente mayor que la de los gráficos ráster digitales (1.62 km/km$^2$) y más del doble que la de los gráficos lineales digitales (1.21 km/km$^2$) y TIGER (1.27 km/km$^2$). La mayor densidad de caminos en los gráficos ráster y las ortofotos se debió principalmente a la adición de caminos menores. Cuando se usaron todos los caminos para definir límites de los parches, las medidas del paisaje obtenidas con datos de ortofotos mostraron niveles de fragmentación significativamente mayores que las basadas en gráficos ráster o lineales. Por ejemplo, el tamaño máximo de parche fue 1074*

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*ha y el borde total fue 109 km en el gráfico lineal, comparado con 686 ha y 211 km para datos de ortofotos. Hay caminos ausentes en los datos usados comúnmente porque los estándares de mapeo sistemáticamente excluyen a los caminos menores. Estos estándares no tienen bases ecológicas y pueden llevar a suposiciones falsas acerca de los efectos ecológicos de caminos. Recomendamos que futuros estudios den especial consideración a la integridad de datos de caminos y consideren si todos los caminos ecológicamente relevantes están incluidos.*

**Palabras Clave:** densidad de caminos, ecología de caminos, fragmentación, gráfico lineal digital, gráfico ráster digital, modelos de hábitat, ortofoto digital, patrón del paisaje

## Introduction

Roads inflict strong ecological effects on the environment (e.g., Forman & Alexander 1998; Forman et al. 2003). Habitat is directly removed during road construction (Forman 2000). Once constructed, roads present a physical and chemical environment different from that of surrounding areas (Trombulak & Frissel 2000) and alter hydrology by interrupting and redirecting flows of ground and surface water (Wemple et al. 1996). Heavy-metal and salt concentrations are often greater in adjacent roadsides because of vehicle emissions and road-management activities (Forman & Alexander 1998). Roadsides can be dispersal corridors for invasive species (Parendes & Jones 2000). Vehicle collisions resulting in species mortality may contribute to population declines (Oxley et al. 1974; Fahrig et al. 1995; Gibbs & Shriver 2002). Roads are the primary means of access for human use of adjacent areas, and they influence patterns of settlement and land-use change (Pedlowski et al. 1997; Wear & Bolstad 1998).

At the landscape scale, roads cause fragmentation by removing habitat and creating high-contrast edges in otherwise continuous vegetation (Miller et al. 1996; Reed et al. 1996). Habitat fragmentation can cause a change in species composition, especially declines in area-sensitive species or those with limited dispersal capabilities (Saunders et al. 1991; Andrén 1994). In general, as road density increases, mean patch size decreases and total edge increases. In some cases, patch shape complexity either increases (McGarigal et al. 2001) or becomes more simplified (Saunders et al. 2002), with the exact effect of roads depending on their spatial pattern (Miller et al. 1996; Reed et al. 1996).

Existing studies of the effects of roads on landscape structure have used a variety of road data sources (Table 1). These studies may have been based on incomplete road data sources that substantially underestimate road density and habitat fragmentation. Visual comparison of sources of road data show substantial differences in the type and extent of roads represented (Fig. 1). Little quantitative information is available about the specific types and amount of roads missing from current data sources. These differences in the type and density of missing roads are important because different types of roads have varying impacts on the ecological processes they affect (Forman & Deblinger 2000), and when considered over an entire road network these ecological effects may contribute substantially to habitat fragmentation (Miller et al. 1996; Reed et al. 1996).

**Table 1. Existing studies of the effects of roads on landscape structure and the researchers' source of road data.**

| *Publication reference* | *General topic* | *Road data source* |
|---|---|---|
| Mladenoff et al. 1995 | wildlife | TIGER |
| Saunders et al. 2002 | fragmentation | |
| Stoms 2000 | wildlife | |
| Cardille et al. 2001 | fire | 1:100,000-scale maps |
| Clark et al. 1993 | wildlife | |
| Heilman et al. 2002 | fragmentation | |
| Jones et al. 2001 | hydrology | |
| Tinker et al. 1998 | fragmentation | |
| Woolf et al. 2002 | wildlife | |
| Brody & Pelton 1989* | wildlife | 1:24,000-scale maps |
| Lovallo & Anderson 1996 | wildlife | |
| Miller et al. 1996 | fragmentation | |
| Reed et al. 1996 | fragmentation | |
| Wear & Bolstad 1998 | land use/land cover | |
| Jennings & Jarnagin 2002 | hydrology | air photos |
| Jones & Grant 1996 | hydrology | |
| Mace et al. 1996 | wildlife | |
| McGarigal et al. 2001 | fragmentation | |
| McLellan & Shackleton 1988 | wildlife | |
| Wemple et al. 1996 | hydrology | |

** U.S. Forest Service transportation maps.*

Examining different sources of road data, in terms of the type and amount of roads represented, can provide information as to what data is lacking in current road coverages and which data sources are most appropriate for which ecological questions. However, there is a potential trade-off between data sources in terms of the completeness of the data represented and the cost to obtain it. Coarse road data may not include all roads but are readily available from the U.S. Geological Survey (USGS) or U.S. Census Bureau. Detailed road data, developed from interpretation of aerial photographs, are more complete but require a significant investment in time and labor. It

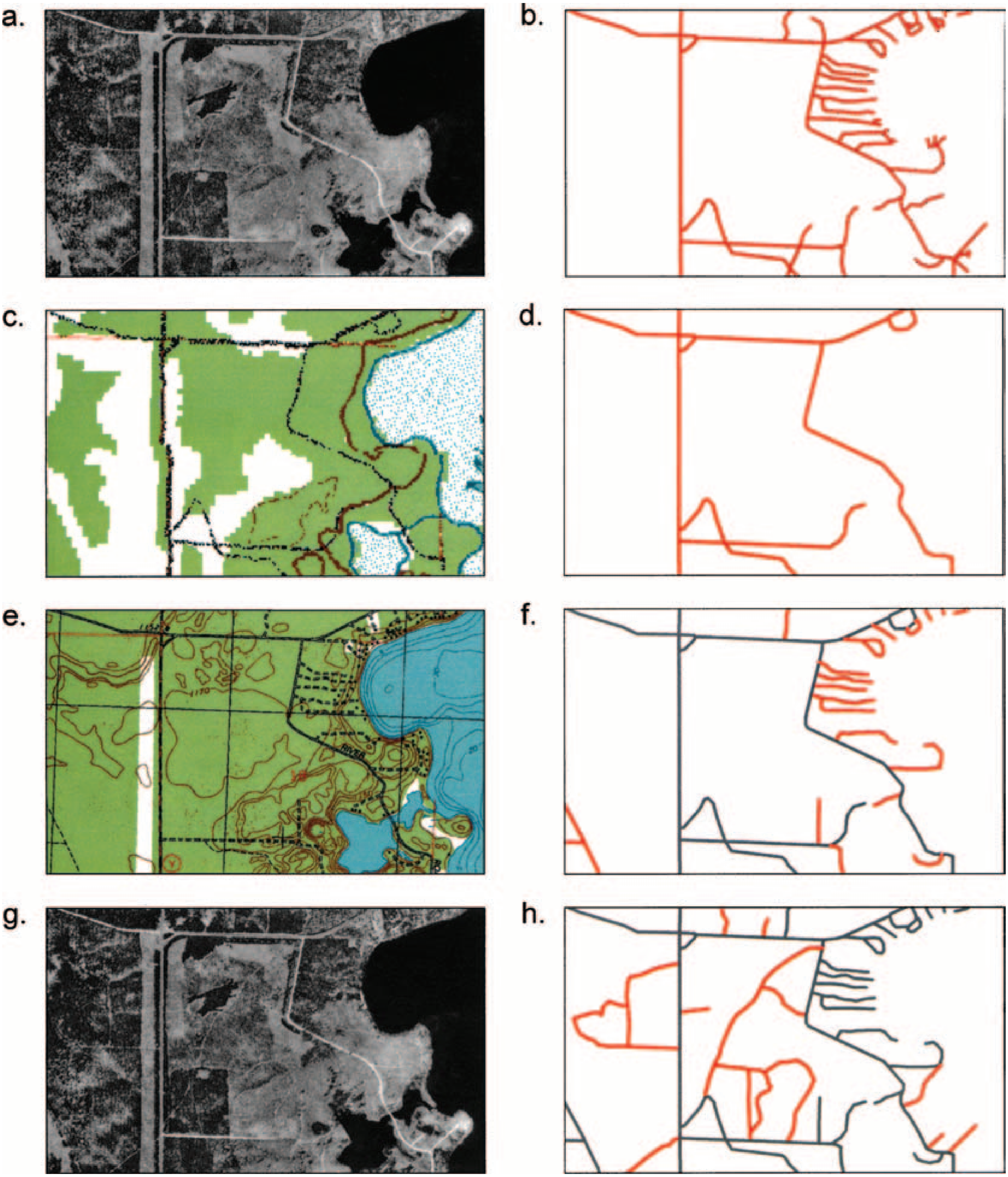



*Figure 1. Examples of the four road data sources: (a) 1:40,000-scale digital orthophoto quarter quadrangle (DOQQ); (b) U.S. Census Bureau TIGER road data; (c) 1:100,000-scale U.S. Geological Survey topographic map; (d) digital line graph (DLG) road data; (e) 1:24,000-scale U.S. Geological Survey topographic map; (f) both 1:100,000-scale DLG roads in gray and 1:24,000-scale digital raster-graphic roads (DRG) in red; (g) 1:40,000-scale DOQQ; (h) DLG and DRG roads combined in gray and DOQQ roads in red.*

**Table 2. Road class descriptions for digital line-graph and digital raster-graphic data (U.S. Geological Survey [USGS] 1998) and census feature class codes (CFCC) for TIGER line files (U.S. Census Bureau 2002*a*).***

| *Data source* | *Road class* | *Mean road width (m)* | *Standard deviation (m)* | *Description* |
|---|---|---|---|---|
| USGS | 1 | 32.0 | 14.3 | hard-surface highways, including interstate U.S. numbered highways (including alternates), primary state routes, and all controlled-access highways |
| USGS | 2 | 32.0 | 14.3 | hard-surface highways, including secondary state routes, primary county routes, and other highways that connect principal cities and towns and link these places with the primary highway system |
| USGS | 3 | 15.7 | 7.9 | hard-surface roads not included in a higher class and improved loose-surface roads passable in all kinds of weather; these roads are adjuncts to the primary and secondary highway systems; also included are important private roads such as main logging or industrial roads that serve as connecting links to the regular road network |
| USGS | 4 | 9.9 | 5.3 | unimproved roads that are generally passable only in fair weather and are used mostly for local traffic; also included are driveways, regardless of construction |
| USGS | 5 | 4.8 | 1.9 | unimproved roads passable only with 4-wheel-drive vehicles |
| TIGER | A1 | 42.0 | 30.27 | interstate highways and some toll highways |
| TIGER | A2 | 25.0 | 11.36 | mainly U.S. highways but may include some state and county highways that connect cities and larger towns |
| TIGER | A3 | 25.0 | 11.36 | includes mostly state highways but may include some county highways that connect smaller towns, subdivisions, and neighborhoods |
| TIGER | A4 | 8.0 | 5.09 | a road used for local traffic; in an urban area, this is a neighborhood street that is not a thoroughfare; in a rural area, this is a short-distance road connecting the smallest towns; scenic park roads, unimproved or unpaved roads, and industrial roads; most roads in the nation are classified as A4 roads |
| TIGER | A5 | 8.0 | 5.09 | a road usable only by four-wheel-drive vehicles, usually a one-lane dirt trail and found almost exclusively in very rural areas; includes fire roads, logging roads, and may include abandoned railroad grades; minor, unpaved roads usable by ordinary cars and trucks belong in category A4 |
| TIGER | A6 | 8.0 | 5.09 | roads, portions of a road, intersections of a road, or the ends of a road that are parts of the vehicular highway system and have separately identifiable characteristics |
| TIGER | A7 | 8.0 | 5.09 | roads that are not part of the vehicular highway system, including foot and hiking trails located on park and forest land, as well as stairs or walkways that follow a road right-of-way and have names similar to road names |

**Road width was measured by road class from 30 randomly selected points along roads in aerial photographs. The mean width of class 1 and 2 roads were within 2 m of each other and thus combined, TIGER roads of class A2 and A3, and A4, A5, A6, and A7 were also combined.*

is unclear to what extent road density and landscape fragmentation depicted by coarse data are correlated with measures based on detailed road data.

Finally, it is important to determine whether roads are missing because of outdated maps or because they were not mapped. The age of current road data may be especially important in areas where there has been recent road construction as a result of housing development and logging activity (Wade et al. 1999). The standards used to define a road and whether or not it is mapped may also have an effect. U.S. Geological Survey rules for inclusion of roads dictate that major roads (classes 1, 2, and 3; Table 2) are always mapped, but unimproved roads (classes 4 and 5) are only mapped if they lead to other mapped features or are part of the most permanent and direct routes (USGS 1980; Wade et al. 1999).

Our objectives were to quantify differences in road density and resulting fragmentation among road data sources. We set out to determine whether road density is significantly different among data sources and what types of roads account for differences in road density among data sources. Focusing on the landscape patterns created by roads, we tested whether landscape patterns created by roads differ among data sources and among road classes within each data source. We determined whether more detailed road data can be predicted based on existing coarse-scale road data by measuring the correlation in road density and landscape patterns among the data sources. Finally, we explored the reasons for the differences in road data sources and determined whether roads were missing mainly because of outdated map sources or mapping standards.

## Methods

### Study Area

Our study area was the forested region of northern Wisconsin (U.S.A.) or, more specifically, all Wisconsin counties in the Laurentian Mixed Forest Ecoregion Province

(Wisconsin Department of Natural Resources [WDNR] 1999). Counties with 60% or less forest cover as estimated from the WISCLAND land-cover map (WDNR 1998) were not included. Sampling units were USGS digital orthophoto quarter quadrangles (DOQQ), which correspond to one-quarter the area covered by a USGS 1:24,000-scale topographic map (USGS 1996) or approximately 3500 ha. Within each county, we randomly selected quarter quadrangles covering approximately 10% of the county's area, resulting in a total sample of 144 quarter quads.

Land ownership is a mix of 15% county forests (Wisconsin County Forests 2003), 5.5% state land (WDNR 1997), 16% national forest (U.S. Forest Service 2001), and 4.5% tribal nations (J. Coleman, personal communication). The remaining 59% is privately owned by both timber industries and individuals.

### Sources of Road Data

We compared four road data sources for northern Wisconsin: (1) USGS 1:100,000-scale digital line graphs (DLGs), (2) USGS 1:24,000-scale digital raster graphics (DRGs), (3) U.S. Census Bureau TIGER line files, and (4) a data set derived from digital orthophotos (DOQQs). The geographic information system (GIS) data sets for DLG and TIGER are readily available for most of the United States. The DRG and DOQQ data sets also have extensive coverage but require that roads be manually digitized from imagery before being used in a GIS.

Digital line graphs are vector coverages of features, such as roads, railroads, and hydrology, present in the 100,000-scale topographic map series produced by the USGS (1998). This map series was last revised between 1979 and 1986 for northern Wisconsin (WDNR 1990*a*). We used DLG road data as an individual data set and as a base coverage to which roads from additional data sources were added.

More detailed 1:24,000-scale DLG data exist only for select areas in northern Wisconsin (USGS 2002). However, complete coverage exists in the form of digital raster graphics, which are georeferenced digital images of the 1:24,000-scale USGS topographic map series published between 1962 and 1984 for northern Wisconsin (WDNR 1990*b*). We digitized roads in raster graphics that were not already present in the line graphs. We assumed that all roads in the line graphs exist in the raster graphics. All additional mapped roads were assigned a road class (Table 2) based on their classification in the topographic maps.

U.S. Census Bureau TIGER line files were developed for the decennial census (U.S. Census Bureau 2002*a*) and include road coverage for the entire United States. Initially, these road data were developed from the 1:100,000-scale USGS digital line graphs; updates were made for the 1990 and 2000 censuses. We used TIGER 2000 road data as the third road data source for this study (U.S. Census Bureau 2002*b*).

Aerial photography is the original information source for most road maps produced by the USGS (1998). The most commonly available air photos are the 1:40,000-scale black and white series from the North American Photography Project (NAPP). Digital orthophoto quarter quadrangles are scanned and orthorectified NAPP photos covering one-quarter of a 1:24,000-scale, 7.5-minute USGS topographic map with 1-m pixel resolution (USGS 1996). We used orthophotos dating from between 1986 and 1999. Starting with the combined line graph and raster graphic road data, we digitized additional roads visible in the air photos. We considered roads to be any linear feature connected to existing roads with clear evidence of vehicular use. Driveways <50 m long were assumed to be ecologically insignificant and were not mapped. All additional roads mapped from the DOQQs were assigned a road class following the USGS road classification system (Table 2).

### Comparison of Road Density

Among the four road data sets, we compared mean road density of the 144 sampled quarter quads. We used only terrestrial land area in road-density calculations. Differences in mean road density were tested for significance with a one-way analysis of variance (ANOVA) with a least-significant-difference comparison of means among data sources. Similarly, we also compared road density by road class for the DLG, DRG, and DOQQ data.

We did not include TIGER in the comparisons of road class because it follows a different road classification system (Table 2). Positional differences of up to 100 m in the data introduced by subsequent updates and processing further complicated direct comparison of TIGER with other road data. We compared the percentage of roads missing in TIGER data but included in DLG data by measuring the length of TIGER roads falling outside a 50-m buffer of the DLG roads. Similarly, to quantify the percentage of roads in TIGER data but not present in DLG data, we calculated the percentage of DLG roads falling outside a 50-m buffer of the TIGER roads. We made no statistical tests among road types because TIGER roads are classified according to a different system than the DLG data, and even though the classifications are qualitatively similar, there is limited agreement between the data. For example, a road classified as an A4 road in TIGER data may be a class 3, 4, or 5 road in the DLG data (Table 2; Fig. 2).

### Comparison of Landscape Pattern

We examined the effects of different types of roads on landscape pattern by grouping roads into three combinations according to road class: classes 1–3, 1–4, and 1–5 for

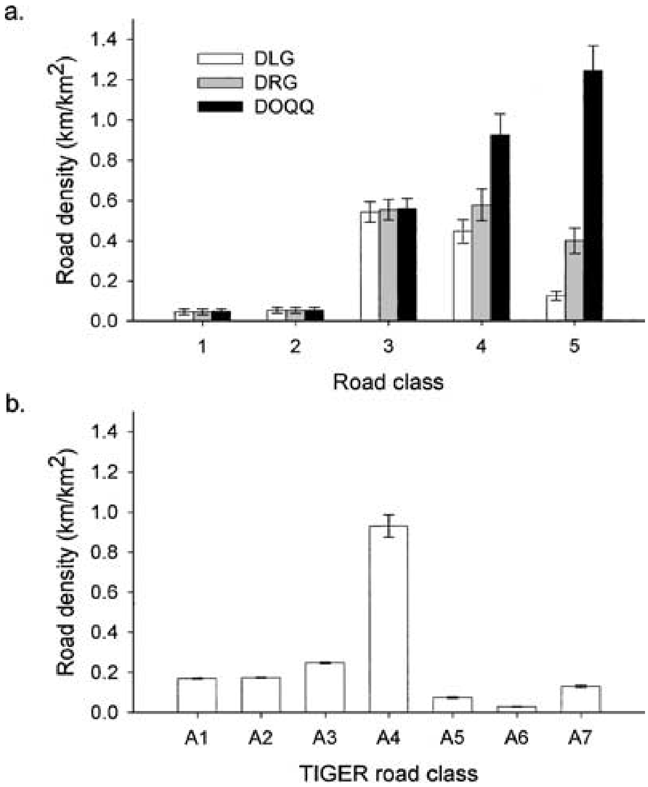



*Figure 2. (a) Mean road density by road class (Table 2) for 1:100,000-scale digital line-graph (DLG), 1:24,000-scale digital raster-graphic (DRG), and 1:40,000-scale digital orthophoto quarter quadrangle (DOQQ) road data. (b) Mean road density by road class for TIGER data. Error bars show 95% confidence interval of the mean.*

USGS and aerial photo data. Roads were buffered according to road class, and a sample of road widths were measured from aerial photographs (Table 2). We measured road width at 30 randomly selected points along roads of each road class. In rural areas, we measured width from forest edge to forest edge or from the outside edges of road ditches. In towns and other populated areas, we measured road width from the edges of the road. Width measurements for road classes 1 and 2 were not significantly different and thus were combined. TIGER classes A2 and A3 and classes A4, A5, and A7 were combined similarly. Because road classes are not equivalent between TIGER and USGS data, the comparisons with TIGER landscape patterns were made using all roads in the TIGER data set. This methodology results in measures of the area affected by the roadway. It is a conservative estimate of the area affected by roads because the ecological effects of roads often extend beyond the immediate roadway (Forman & Deblinger 2000).

After roads were buffered, we calculated landscape metrics for terrestrial patches remaining outside the road buffers. Patches were not further defined by different cover types (i.e., forest, grassland, wetland, agriculture) and could have included a mixture of cover types. Metrics calculated for each quarter quad included sum of patch areas (ha), maximum patch area (ha), sum of patch perimeter (km), mean patch area (ha), and area-weighted mean shape index. We averaged metrics for each road data source. Sum of patch area was inverse-transformed and mean patch area log-transformed to achieve normal distributions. We analyzed differences in metrics among road data sources and road class combinations with one-way ANOVAs and least-significant-difference comparison of means.

### Relationships between Sources of Road Data

The trade-off between data completeness and availability of road data could potentially be overcome if road densities mapped from aerial photographs could be predicted from existing road data, such as DLG or TIGER. We explored relationships among data sources through a correlation analysis of TIGER, DLG, DRG, and DOQQ road density.

Depending on the specific arrangement of roads on the landscape, fragmentation may increase or remain relatively constant as road density increases (Miller et al. 1996). To determine whether the level of landscape fragmentation depicted by road data from more detailed aerial photographs can be approximated from existing, less detailed road data, we correlated the landscape patterns created by all roads among TIGER, DLG, DRG, and DOQQ data.

### Reasons for Differences in Road Data

Observed differences between data sources could be due to both mapping standards and new road construction that has occurred between the dates of map publication and aerial photography. We used simple linear-regression models relating the difference in the density of all roads to the difference in date between data sources to determine which cause is more prevalent. A positive correlation between difference in road density and difference in date would suggest additional road construction over time as the major cause. A lack of correlation would suggest that differences were due to mapping standards.

## Results

### Comparison of Road Density

The most commonly used road data—TIGER, 1:100,000-scale DLG, and 1:24,000-scale DRG—showed significantly lower road density than roads mapped from digital aerial photographs or DOQQs. Road density from DOQQ data (2.82 km/km$^2$) was more than twice that of TIGER and DLG data (1.27 km/km$^2$ and 1.21 km/km$^2$, respectively).

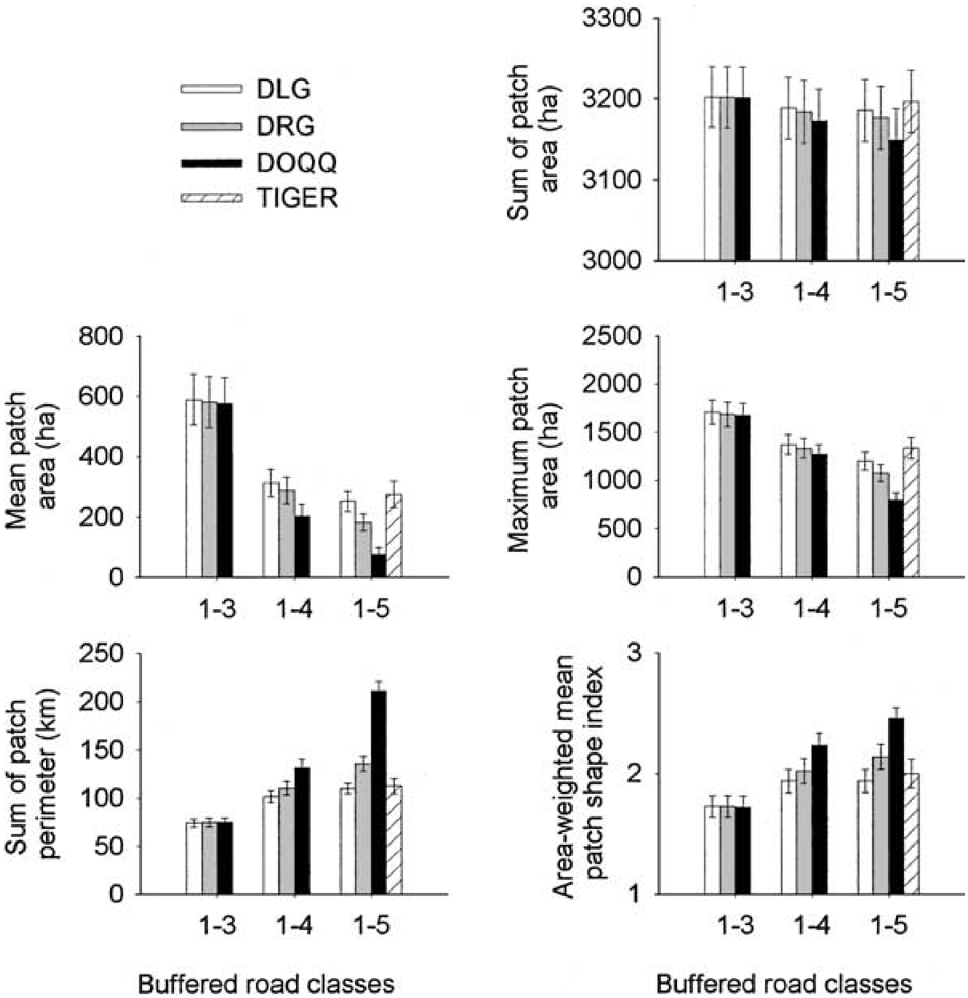



*Figure 3. Landscape metrics of terrestrial patches outside four different road data sources buffered according to road class (Table 2): 1:100,000-scale digital line graphs (DLG), 1:24,000-scale digital raster graphics (DRG), 1:40,000-scale digital orthophoto quarter quadrangles (DOQQ), and 2000 TIGER line files. Error bars show 95% confidence interval of the mean.*

When mapped from 1:24,000-scale DRGs, total road density was 1.62 $km/km^2$. The increases in road density in DOQQ and DRG data were largely a result of the addition of class 4 and 5 roads not included in DLG data (Fig. 2). Both DRG and DOQQ data contained significantly greater densities of class 5 roads than DLG data. Differences in class 4 road density among the data sources were only significant for the DOQQ data. Densities of major roads (classes 1–3) were not significantly different among the three data sources.

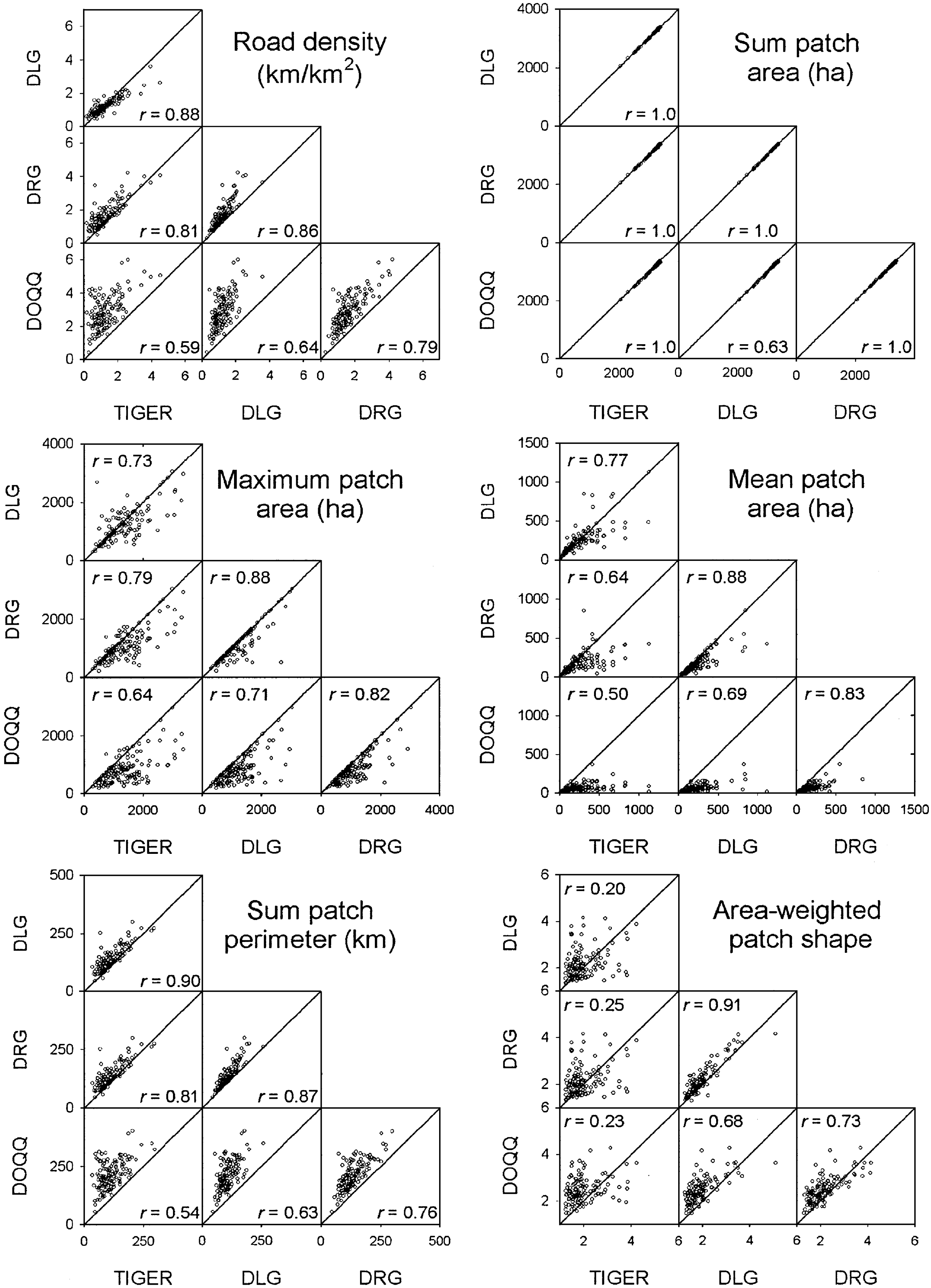
Although road density was not significantly different between DLG and TIGER data, the two data sets are not identical. Seventeen percent of DLG roads fell outside the 50-m buffer of TIGER roads, 40% of those being class 4 roads and 56% class 5 roads. Eighteen percent of roads in the TIGER data fell outside the 50-m buffer of DLG roads; the majority of which were A4 and A7 roads (73% and 20%, respectively).

### Comparison of Landscape Pattern

Increases in class 4 and 5 road density in DRG and DOQQ data resulted in significantly greater levels of landscape fragmentation (Fig. 3). The differences in landscape pattern varied among data sources and depended on the classes of roads used to define patch boundaries. However, one metric, sum of patch areas, varied little within and among all data sources. This is likely a result of the small widths chosen to buffer roads (Table 2).

Because the density of roads of class 1, 2, or 3 did not vary among data sources, there were no significant differences among data sources in any of the landscape metric comparisons when we used buffers of class 1, 2, and 3 roads to define landscape pattern. When class-4 roads were included, the landscape became much more fragmented. Mean and maximum patch area decreased, whereas the sum of patch perimeter and the area-weighted index of mean patch shape increased. All these differences were significant within data sources (e.g., DLG 1–3 vs. DLG 1–4), except sum of patch areas. However, among data sources (e.g., DLG vs. DRG) the differences in landscape metrics with the addition of class-4 roads were significant only for the DOQQ data.

Including class-5 roads in the buffers produced a more fragmented landscape for DRG and DOQQ data. These differences were most pronounced for the DOQQ data,


Road density
(km/km2)
r = 0.88
r = 0.81
r = 0.86
r = 0.59
r = 0.64
r = 0.79
Sum patch
area (ha)
r = 1.0
r = 1.0
r = 1.0
r = 1.0
r = 0.63
r = 1.0
Maximum patch
area (ha)
r = 0.73
r = 0.79
r = 0.88
r = 0.64
r = 0.71
r = 0.82
Mean patch
area (ha)
r = 0.77
r = 0.64
r = 0.88
r = 0.50
r = 0.69
r = 0.83
Sum patch
perimeter (km)
r = 0.90
r = 0.81
r = 0.87
r = 0.54
r = 0.63
r = 0.76
Area-weighted
patch shape
r = 0.20
r = 0.25
r = 0.91
r = 0.23
r = 0.68
r = 0.73
DLG
DRG
DOQQ
TIGER
DLG
DRG

which contained by far the greatest density of class-5 roads (Fig. 3). For instance, mean patch area dropped from 138 ha in the DRG data to 53 ha in the DOQQ data, and sum of patch perimeter rose to 210.5 km from 135 km in the DRG data. Within the DLG data, only maximum patch area decreased significantly when class-5 roads were included in the buffers.

### Relationships among Sources of Road Data

We used scatter plots and calculated correlation in road density between data sources to determine whether road density, measured from detailed topographic maps (DRGs) and aerial photographs (DOQQs), is related to less-detailed road data, such as 1:100,000-scale DLG data. There was a general linear relationship between road densities for all four data sources compared: TIGER, DLG, DRG, and DOQQ (Fig. 4). Correlation in road density was greatest when the two data sources had a similar origin, mapping standards, and scale, such as DRG compared with DLG and DLG compared with TIGER. However, existing data sources (TIGER and DLG) captured less than half of the variation in DOQQ road density (34% and 41%, respectively).

Similar trends existed between landscape metrics for TIGER, DLG, DRG, and DOQQ data (Fig. 4). As expected, measures of landscape pattern were most closely correlated between data sources of similar origin and mapping standards (DRG and DLG or DLG and TIGER) and the most dissimilar data were least correlated (e.g., TIGER vs. DOQQ). Except for sum of patch area, DLG and TIGER data captured only a small portion of the variation in DOQQ data (Fig. 4).

### Reasons for Differences in Road Data

To determine whether the differences in road density (all road classes) observed between DLG, DRG, and DOQQ data were related to the date of the original data source, we developed two linear-regression models. Both models were significant, but there was little correlation between the road-density difference and date difference between data sources. Linear regression between the difference in DOQQ and DLG road density over time showed very weak correlation ($r^2 = 0.07$, $F = 11.17$, df = 1 and 142, $p = 0.001$), and the regression of the difference in DOQQ and DRG road density against time was even less correlated ($r^2 = 0.02$, $F = 3.126$, df = 1 and 142, $p = 0.0215$).

## Discussion

Our main finding was that current road data substantially underestimate road density. We calculated road density in northern Wisconsin at 2.82 km/km$^2$ after mapping all roads visible from aerial photographs. Previous estimates of paved road density were much lower: 1.1 km/km$^2$ for northern Wisconsin (Saunders et al. 2002) and 1.2 km/km$^2$ for the entire United States (Forman 2000). The differences in road density were largely a result of the addition of many class 4 and 5 or minor roads. These roads are lake- and cabin-access roads, logging roads, and four-wheel-drive trails, clearly visible as such in aerial photographs but largely missing in commonly available road data sets.

At the landscape level, both major and minor roads cause a reduction of interior habitat area and an increase in edge. When we used roads mapped from aerial photographs to define landscape pattern, the result was a much greater level of fragmentation than previously suggested by existing road data sources. The largest patch without roads was 682 ha, and the average patch without roads was approximately 53 ha. In estimates provided by current road data, such as USGS 1:100,000-scale DLG, maximum patch area was 1078 ha and mean patch area 138 ha. Total edge more than doubled from 109 km/quarter quad with DLG data to 210 km/quarter quad for road data from aerial photographs (DOQQ). Area-weighted patch shape increased from 1.93 to 2.45, indicating that the shape of patches without roads became more convoluted and complex with the addition of class 4 and 5 roads.

The increase in landscape fragmentation by the additional minor roads has implications for biodiversity and ecosystem management, especially for species with limited migration (Saunders et al. 1991) or requirements of large areas of interior habitat (Andrén 1994). Many researchers have focused on the effects of major roads, but the minor roads we mapped may have substantial ecological effects and should be considered in broad-scale studies of the impacts of roads.

### Effects of Minor Roads

Minor roads have a wide range of ecological effects (Forman & Alexander 1998; Forman et al. 2003). Logging roads interrupt subsurface water flows, converting them to surface flows, and redirect that flow to streams, thus increasing peak flows and causing earlier peak-flow times

*Figure 4. Correlations of road density and landscape metrics between road data sources: 1:100,000-scale digital line graphs (DLG), 1:24,000-scale digital raster graphics (DRG), 1:40,000-scale digital orthophoto quarter quadrangles (DOQQ), and 2000 TIGER line files. Road density and landscape metrics were calculated with all road classes (Table 2). Landscape metrics were calculated on terrestrial patches remaining outside buffers of all roads(buffer distance was determined according to road class) (Table 2).*

(Jones & Grant 1996; Wemple et al. 1996). For small vertebrates, minor roads can act as a source of mortality and pose barriers to movement (Oxley et al. 1974; Mader 1984; Fahrig et al. 1995). However, large carnivores may use small roads as movement corridors (Brody & Pelton 1989). Minor roads and even hiking trails may affect bird abundance and species composition (Rich et al. 1994; Miller et al. 1998). Gaps created by roads in the forest canopy are utilized by nest parasites (Rich et al. 1994; Gates & Evans 1998; Miller et al. 1998) and predators (Chalfoun et al. 2002; Rodewald 2002), thus reducing breeding success and species abundance. Minor roads also affect plant diversity at both broad and fine scales (Brosofske et al. 1999) because the canopy gaps created by roads increase light levels, which in combination with traffic and road maintenance make roadways suitable for exotic and invasive species (Parendes & Jones 2000; Watkins et al. 2003).

At local scales, the ecological effects of minor roads may appear as scratches in the sand; for instance, exotic species may be limited to a 15-m zone around minor roads (Watkins et al. 2003) compared with a 120-m zone around improved roads (Forman & Deblinger 2000). When the effects of minor roads are extrapolated across their extensive network, however, the result is a great reduction of undisturbed interior area. Our results show that substantial fragmentation is caused by roads even when only the width of roads is used to define the areas disturbed by road. The extent of the fragmentation would have increased if even greater road-effect zones were assumed.

### Methodological Considerations

Although much greater than those based on existing data sources, our estimates of road density may still be an underestimate. The visibility of roads in aerial photographs is not equivalent for all forest types, depending on crown structure and canopy closure over the road. Deciduous forests with closed canopy structures could conceivably cover roads and make them undetectable, especially during seasons in which trees are fully leafed out. The aerial photographs we used were taken when trees were leafing out in northern Wisconsin, which may have occluded some roads. We used caution when mapping roads from aerial photographs, with the criteria that new roads be connected to existing roads and create a clearly visible canopy gap. With these criteria, some roads visible in the air photos were not mapped because it was not possible to trace their path back to the main road network.

Patterns of road density vary across northern Wisconsin and appear to be more closely related to patterns of housing density and soil substrate than to forest or other land-cover types. Our results related to increases in fragmentation resulting from the addition of class-4 roads are probably representative of many rural areas that have experienced rapid housing growth, whereas the greater density of class-5 roads and consequent fragmentation is likely common throughout forested areas under timber management. Our findings should not be extrapolated to places with different land-use contexts, however, such as expanding urban areas or places where a substantial proportion of the land is in agricultural production. Compared with northern Wisconsin, those areas are likely to have a much different road network with more permanent roads and fewer class-5 roads, making it more likely that readily available data includes all roads.

Our buffer widths were chosen conservatively and contained only the immediate road-affected area. They therefore may not represent the entire road-effect zone, which can extend up to several hundred meters beyond the roadway (Forman & Deblinger 2000). Also, the roadless patches we used for comparing landscape pattern may represent an underestimate of landscape fragmentation. We considered patches to be homogenous roadless habitat, but realistically they are composed of a mixture of different forest types, wetlands, and agriculture (Mladenoff et al. 1993; Saunders et al. 2002). Had patches been defined based on both roads and land cover, the level of fragmentation would likely have been even greater (Miller et al. 1996; Saunders et al. 2002).

### Comparison of Sources of Road Data

There is a trade-off between the availability of road data and its completeness. Current sources of road data, such as TIGER or DLG, can be used with a minimal investment in time and resources, but they lack the completeness and may not capture the landscape patterns imposed by the actual road network. Road density and landscape metrics among TIGER, DLG, DRG, and DOQQ data were correlated (Fig. 4). The sum of patch areas was most strongly correlated among different data sources, and patch shape was least correlated. However, the strength of the relationship was weakest between DOQQ data and other road data (DLG or DRG), explaining only a small portion of the variation. We recommend that future investigators consider using more accurate road data than provided by current road-data sources in cases where the effects of minor roads are important.

Mapping standards appear to be the primary reason for the discrepancy among the four road data sources. Maps published by the USGS are designed primarily for transportation, and the main purpose of census data is to define the boundaries of census blocks. Specific rules to determine whether or not a road is included are used by the USGS during map production (USGS 1980); as a result, many roads are not included. This suggests that the differences we observed in road density are largely a result of mapping standards and that the problem of missing roads is not likely to be solved with updated maps.

## Conclusions

Commonly available digital road data may miss up to 50% of the roads in the landscape and may significantly underestimate landscape fragmentation. The TIGER and DLG data sets are readily available and free, which may contribute to their common use in ecological studies (Table 1). These data were not developed for ecological research, however, and do not include the majority of minor roads that are likely to be important in studies of the effects of habitat fragmentation on invertebrates, amphibians, reptiles, invasive-species spread, hydrology, stream sedimentation, and the recreational use of forests. Designers of future studies on the effects of roads on the environment need to carefully determine whether all roads relevant to the ecological question under investigation are included in the source data.

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