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Research Paper

Challenges in characterizing a parcelized forest landscape: Why metric, scale, threshold, and definitions matter

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HIGHLIGHTS

- ► Our analyses of four different parcelization metrics show that each metric often describes a different pattern of forest parcelization.
- ► Each metric appears to capture different aspects of ownership patterns within a forest landscape.
- ► The choice of parcelization metric, scale, and threshold can greatly influence the resulting parcelization story.
- ► Careful consideration must be given to these factors when attempting to analyze a parcelized landscape.
- ► Caution is urged in interpreting and comparing parcelization studies that use differing metrics and/or scales.

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ABSTRACT

Several metrics have been cited in the literature as being useful characterizations of forest land parcelization. Yet no agreed-upon standard measure exists which creates difficulties in identifying where parcelization is occurring as well as comparing the magnitude of its occurrence across different studies and geographic regions. We evaluated three existing (average parcel size, Gini coefficient, Shannon Entropy index) and a new metric (adjusted mean parcel size) for their usefulness in characterizing the extent to which a private forested landscape has become parcelized. We applied these measures to 410 forested townships in a contiguous, six-county area of northern Minnesota encompassing nearly 3.64 million hectares. Our analyses show that each metric typically describes a different pattern of parcelization and highlight problems owing to the fact that each metric appears to capture different aspects of ownership patterns within a landscape. We demonstrate the choice of metric, landscape scale, spatial and physical ownership features, and threshold for determining when a landscape is parcelized can greatly influence our conclusions regarding parcelization. Thus, careful consideration must be given to these factors when attempting to analyze a parcelized landscape, and caution is urged in interpreting and comparing parcelization studies where one or more of these factors vary.

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1. Introduction

Parcelization of private forest land, the fragmentation of forest ownership into smaller blocks, is a growing policy concern (Kilgore & MacKay, 2007). Forest land parcelization has been shown to be associated with the loss of wildlife habitat and timber availability, diminished water quality, and greater restrictions on recreational access (Greene, Harris, DeForest, & Wang, 1997; King & Butler, 2005; LaPierre & Germain, 2005; Mehmood & Zhang, 2001; Rickenbach & Gobster, 2003; Romm, Tuazon, & Washburn, 1987; Straka, Wisdom, & Moak, 1984; Theobold, Miller, & Hobbs, 1997; Wear, Turner, & Naiman, 1998). Parcelization has also been described as a forerunner to forest fragmentation and development (e.g., Germain, Brazill, & Stehman, 2006; Sampson & DeCoster, 2000; Thorne & Sundquist, 2001; Zipperer & Birch, 1993). The USDA Forest Service projects the U.S. could lose approximately 6 million hectares of forest land from 2002 to 2050, primarily to residential development (Haynes et al., 2007). If forest land is developed, many of the forest-based goods and services are permanently lost.

Despite myriad concerns about the adverse impacts from parcelization, there is no agreement on how to tell when or if a landscape has become parcelized in the first place, or whether it has passed a threshold such that adverse impacts begin to occur.

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Parcelization is often described as 'you know it when you see it.' While policy makers or resource professionals may believe they can identify areas where parcelization has become a concern, a lack of professional agreement and literature on how to empirically quantify it ultimately confounds efforts to devise policies or programs to prevent parcelization from occurring.

We argue that the choice of metric can greatly influence how a landscape is described and interpreted relative to parcelization. Average parcel size has typically been the metric reported when describing a parcelized landscape, with the presumption that a lower average parcel size is an indicator of greater parcelization. However, mean has been shown to have some shortcomings as a parcelization metric (Kittredge, D'Amato, Catanzaro, Fish, & Butler, 2008; Pan, Zhang, & Majumdar, 2009). A useful parcelization metric should be able to capture several attributes of the landscape, including average parcel size, but also a characterization of the relative number of small or large parcels. In addition, being able to capture these attributes in a single-value measure would permit analysts to rank parcelization activity across a wide geographic range of landscapes. In this paper, we compare four potential single-value parcelization metrics to determine whether they score landscapes consistently with respect to parcelization, and whether they are able to capture landscape and parcel attributes we hypothesize to be related or important to parcelization.

2. Background

Most empirical assessments of forest land parcelization activity are temporal in nature, tracking shifts in the distribution of parcel size classes or individual parcel lineages through time. Drzyzga and Brown (1999) digitized historical parcel maps from plat books at three points in time (1970, 1980, 1990) for three Michigan counties, calculating parcelization as the change in average parcel size between each time period. LaPierre and Germain (2005) conducted a study to empirically quantify forest land parcelization in four New York counties between 1984 and 2000. Their study compared a geographic information system (GIS) file containing digitized parcel boundaries in 2000 to paper maps of the same area created in 1984. They examined changes in the distribution of parcel size classes between these two time periods. Germain et al. (2006) quantified parcelization in one New York county using digital tax map sheets, tracking the total number and area of parcels in six different area classes between 1975 and 2000.

In other studies, life histories of parcels are constructed utilizing "parent and child relationships," the former referring to pre-parcelization and the latter to post-parcelization parcels. Donnelly and Evans (2008) digitized historic plat maps to track ownership changes in two townships in Indiana between 1928 and 1997. A parcelization typology was developed to characterize the different types of parcel split or aggregation events. Haines, Kennedy, and McFarlane (2011) and Kennedy and McFarlane (2009) digitally reconstructed historic tax parcel maps in a GIS for several communities in northern Wisconsin using tabular tax ownership records to identify parent and child parcels. Ownership maps were created by digitizing plat books, paper maps, and legal descriptions from tax assessment rolls to track changes in ownership from 1954 to 2007. Mundell, Taff, Kilgore, and Snyder (2010) used real estate records to examine changes in ownership in forest parcels over time. Rather than using map-based data, this study relied solely upon real estate transaction records. To track changes in parcelization over time, unique parcel identifier numbers and the associated deeded land area were matched in successive years to track all parcelization and subsequent development activity from 1995 to 2006.

In sum, studies describing temporal assessments of forest land parcelization have proven to be very time and labor intensive, owing to the need to digitize paper maps and/or cull through extensive historical tabular records. These studies provide detail on the sequence of ownership change in specific landscapes over time and, in some instances, important drivers of these changes. Yet, these studies do not provide insight into when or where thresholds of parcelization concern may exist, or how to effectively measure the degree or severity of parcelization in a landscape at any point in time.

We are aware of only two nontemporal studies that have focused specifically on measuring the *degree to which* a private forest landscape is parcelized, in contrast to assessments that tracked the *process* of parcelization itself over time. Kittredge et al. (2008) estimated the distribution of private forest parcels and ownership in Massachusetts in different size class categories for a single year. The authors developed a proxy measure of parcelization as the percentage of land in parcels smaller than 8.09 hectares (20 acres). The 8.09 ha threshold was selected because the authors believed it represented a parcel size that was still large enough to support forest management. The authors noted that average parcel size, as a measure of a parcelized landscape, has deficiencies because it can be greatly skewed when a landscape has a large number of small parcels.

Pan et al. (2009) examined the distribution of timberland-holding size at the county-level for 55 counties in Alabama using several metrics: mean county-holding size of forest land, Gini coefficient of county timberland holdings, the percent of county forest land in holdings of fewer than 80 hectares, and percent of county forest land in holdings greater than 800 hectares. Used here, the Gini coefficient measures the distribution of forest land area ownership by comparing cumulative percent of forest land area to cumulative percent of forest land owners (a more formal definition of the Gini coefficient is presented later in the paper). The authors used multiple metrics to evaluate holding size because they contend that average parcel size cannot adequately capture information about the distribution of parcel ownership. The main purpose of their research was to identify socio-economic drivers that influence forest holding size distribution. While both of these studies explored alternative metrics to mean parcel size to evaluate parcelized landscapes, neither illustrated the influence that alternative metrics have when mapped, nor the difficulty in utilizing the metrics to identify areas of parcelization concern on the landscape.

As noted, previous research suggests that average parcel size can be misleading due, in part, to its inability to capture the distributional aspects or structure of parcel holding. To further illustrate, the two landscapes depicted in Fig. 1 contain the same area and number of parcels; hence their average parcel size is identical. However, they portray very different landscapes in terms of parcel shape, size, and arrangement. Many forest-based outputs are a function of tract size (e.g., timber, wildlife habitat, recreation), decreasing in quantity, quality, or economic viability with diminishing tract size. We argue that attributes such as this matter when trying to identify landscapes where parcelization is a concern, yet average parcel size would be indifferent to them.

Another drawback of using mean parcel size to characterize a parcelized forested landscape is its inability to take into account the total amount of private forest within a given landscape. Two forested landscapes can have the same average parcel size but contain very different amounts of private forest land area (e.g., private forests may comprise only 5% of the land base of one landscape, but 95% of the other). Characterizing the degree of parcelization within these two landscapes as equal could mask important aspects with respect to drivers, implications and solutions. For these reasons, we contend that average parcel size does not account for several important factors that characterize a parcelized forest landscape.

We evaluate the ability of three parcelization metrics from the literature (mean parcel size, entropy index, and Gini coefficient)

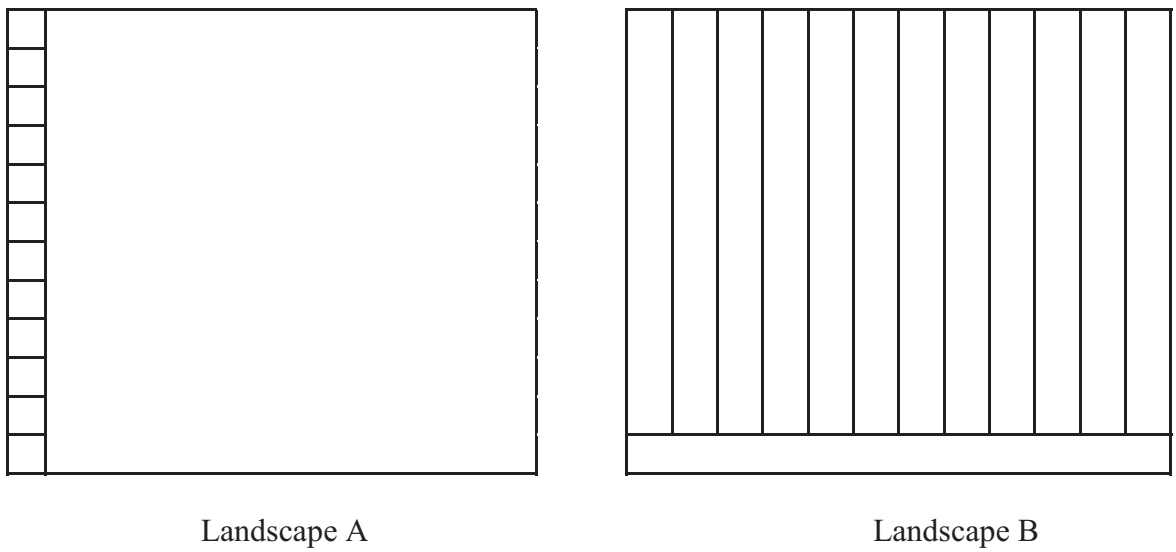

Fig. 1. Two hypothetical landscapes containing the same land area, number of parcels, and mean parcel size.

and one new metric to quantify the degree to which a given landscape is parcelized. Our intent is to show that the choice of metric used to quantify forest land parcelization within a landscape matters, and that relying upon average parcel size may fail to differentiate landscape features which are important when identifying parcelization. We are not aware of any studies that have conducted a comparative analysis to determine how the use of different metrics may influence the resulting characterization of parcelization on a landscape.

3. Data and methods

3.1. Study area database

We examine the extent of "parcelization" across six contiguous northern Minnesota counties, collectively covering 3.64 million hectares of land and water (Fig. 2). This area of northern Minnesota is heavily forested, containing more than 2.45 million hectares of forest land (USDA, 2011). It is also an area where the parcelization of forest land has become an important public policy concern (MFRC, 2010). Digital parcel maps and the associated parcel-level data for these six counties were acquired from the Minnesota Department of Natural Resources in 2009. For each digitized parcel record, the database contained, among other attributes, owner name, owner address, legal description, and parcel boundaries.

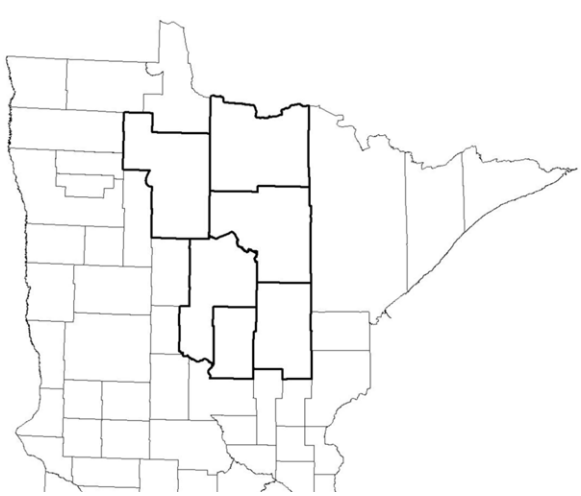

Fig. 2. Six county northern Minnesota study area.

To adapt individual parcel data into the format needed for our analyses, we successively pruned parcel boundary maps that were originally compiled by each county according to county-specific protocols. For each parcel, the owner's name and address, the legal description, and physical boundaries were known. These data, combined with data on current land cover, were sufficient for us to generate the desired private forested parcel maps using the procedures summarized below. These steps were performed in ArcMap, version 9.3.1. (The explicit protocol is available from the corresponding author.)

The first task was to properly identify the size and boundaries of individual land holdings, as opposed to the parcel boundaries shown in official property records. Some counties separate larger forested parcels into individual 16.19 hectare (40 acre) parcels for recording purposes, while others record them as a single parcel. For example, in one county an individual owning 80.94 contiguous hectares (200 acres) of forest land might be shown as "owning" one parcel, whereas in another county an identical 80.94 hectare tract might be recorded as five individual 16.19 hectare (40 acre) parcels. Fig. 3a shows a representative survey township as originally digitized. Parcel boundaries between contiguous parcels with the same owner were eliminated by combining all parcels into single contiguous ownership units based on owner name. This step produced an ownership dataset with a smaller number of parcels. We combined parcels across township lines, but we did not combine them across county lines, enabling us to conduct discrete, county-level analysis where appropriate.

We eliminated all parcels that were less than 0.40 hectares (1 acre) in size, as we felt that correctly assigning a proper land use classification to such small parcels would be extremely difficult, and possibly wrong, given the resolution of available land use data. By eliminating the smallest parcels, we are likely underestimating the extent to which the landscape has been parcelized. Parcels within municipal (e.g., city) boundaries were also removed from the database due to the uncertainty in determining their land cover. Additionally, all publicly owned forest land was eliminated.

Using data from the 30 m USGS National Land Cover database (2006), we assigned each of the more than 100 different land

Fig. 3. Illustration of parcel boundary changes made to identify private forest land parcel boundaries for an example township. In (b), the darker gray area is private forest land, the lighter gray is public forest, and the white is non-forested. In (c), we depict only our parcels of interest: private forest parcels.

use classes into one of five broad categories: forest, annual crops/orchard, grass, water/wetlands, and urban/other. The forest category was used to subsequently identify the private forest lands within the study area. Parcels containing forest cover on at least half of their surface area were retained for further analysis and constituted the private forest parcels in the study area. The minimum 50% forest cover criterion permitted us to select only those parcels where forest constituted a majority of the land cover.

With all public and non-forested lands excluded, we generated our basic unit of analysis: all private forested ownership units in each survey township (an area typically containing 9324 hectares (36 square miles)). We choose survey townships as our unit of analysis because their spatial area is large enough to capture the diversity of private forest land ownership patterns, yet small enough to provide a large number of replications. An example of the resulting maps is shown as Fig. 3b. The darker gray area is private forest land with ownership boundaries shown, the lighter gray area is public forest (with no internal boundaries shown), and the white area is public forest land and non-forest land, including lakes and roads. Note that several smaller parcels in the Fig. 3a are now combined into single ownership parcels. Fig. 3c shows all private forest parcels in an example township with unique, adjacent ownerships. In total, the six-county study area contained 410 survey townships.

3.2. Parcelization metrics

We build upon Kittredge et al. (2008) and Pan et al. (2009) to assess the ways in which four different metrics characterize parcelization in a forested landscape. The four metrics examine here are: Mean parcel size, Entropy, Gini coefficient, and a new metric which we dub "Adjusted Mean."

Mean parcel size (the average size of all private forest land parcels in the landscape) has been used by other researchers to characterize a parcelized forest landscape, as noted above. The Entropy index has been used to quantify other aspects of landscape structure and configuration (e.g., forest fragmentation). The Gini coefficient, which is a measure of parcel size distribution, has also been used to characterize a parcelized forest landscape. The fourth metric, Adjusted Mean, attempts to account jointly for the presence of "many, small" parcels and the amount of private forest area within a landscape.

The Gini coefficient was originally developed to describe inequality of wealth or income in a population (Gini, 1921). It is a widely used metric in the welfare economics literature, but has relevance to other applications in which information is desired about the structure of a distribution. Pan et al. (2009) used a Gini measure to describe timberland ownership holding distribution. The Gini coefficient is the arithmetic average of the absolute value of the difference between parcel size between all pairs in a landscape. Its values range between values of 0 and 1. In a parcelization context, a value of 0 indicates all parcels are equal in size, while a value of 1 indicates all of the forest land in a defined area is in one parcel (i.e., complete inequality in the distribution).

Entropy has been used as a way to measure disorganization of a system (e.g., Lele, Joshi, & Agrawal, 2008), and is defined as: $-\mathrm{SUM}(p^{*}\ln p)$, where p is the parcel size. If the landscape contains only one parcel, Entropy = 0. If all parcels are $1/n$ in size, Entropy = $\ln(n)$. Entropy values increase as the number of parcels of equal size or the total number of parcels increases. Entropy measures arose from the field of information theory as a means to describe the spread or transmission of electronic information (Shannon, 1948). Entropy measures have found application in a diverse set of disciplines, including remote sensing, cartography, geography and landscape ecology, to describe the uniformity (or heterogeneity) of spread of a phenomenon. To our knowledge, Entropy has not been used specifically to assess parcelization, but it has been used to assess urban sprawl patterns (e.g., Li & Yeh, 2004; Rahman, Aggarwal, Netzband, & Fazal, 2011; Sudhira, Ramachandra, & Jagadish, 2004; Yeh & Li, 2001) and land cover fragmentation (Bogaert, Farina, & Ceulemans, 2005; Lele et al., 2008). Both applications use Entropy to quantify aspects of landscape structure and configuration. In the urban sprawl applications, the amount of developed area is measured across a landscape and over time to determine whether development has occurred in more dispersed or compact arrangements (i.e., whether sprawl has occurred). In the fragmentation applications, the proportion of forest area relative to non-forest area is assessed to determine if patch size or pattern diversity is increasing. Extending these concepts, we were interested in determining whether the Entropy index could also be a useful indicator of a parcelized landscape, specifically whether heterogeneity of forest ownership parcel size is an indicator of a parcelized landscape. Lele et al. (2008) suggested that a landscape with complex patch shapes is an indication of patch instability, or fragmentation. We were interested in exploring a corollary idea that a diverse array of parcel sizes might be an indicator of parcelization, or ownership instability.

Table 1
Descriptive statistics for the four parcelization metrics: mean parcel size (Mean), Gini, Entropy, and Adjusted Mean.

Parcelization metric	*N*	Mean	Std Dev	Min	Max
Mean	410	102.53	301.21	1.00	4463.33
Gini	410	0.57	0.18	0.00	0.91
Entropy	410	3.54	1.50	0.00	6.05
Adjusted Mean	410	59.18	111.83	0.00	738.23

The Adjusted Mean metric is one we developed to take into account the spatial extent of small, private parcels and private forest land area in a landscape. It can be represented as

$$\left(\frac{\%\text{ of private forest land in parcels below a parcel size threshold}}{\text{mean parcel size}}\right) \times (\text{private forest land hectares}) \quad (1)$$

which simplifies to

$$(\%\text{ of private forest land in parcels below a parcel size threshold}) \times (\text{number of private forest land parcels}) \quad (2)$$

To address the area presence of small parcels within a landscape, the proportion of parcels within a forested landscape (e.g., township) that are less than a threshold size is included. For our study, we chose 16.19 hectares (40 acres) as the threshold parcel size. Although the selection of a threshold area value is arbitrary, we believe that parcels less than this threshold value could be associated with a parcelized landscape. This threshold size is a smallest parcel delineation unit of the Public Land Survey System, which established the initial parcel boundaries in the U.S. In the Midwestern part of the U.S., 16.19 hectares is a common minimum size for undeveloped forest land in the rural landscapes and a size at which forest management is still possible (Thorne & Sundquist, 2001; Vickery, Germain, & Bevilacqua, 2009). Our 16.19 hectare threshold value is between the 8.09-ha threshold utilized by Kittredge et al. (2008) and the 80-ha threshold utilized by Pan et al. (2009). A higher value of the Adjusted Mean might be thought to represent a higher level of parcelization (i.e., decreasing the average parcel size, increasing the proportion of the landscape in smaller parcels, or increasing the area of the landscape will all increase the value of the Adjusted Mean parcelization metric).

To illustrate the implications of this new metric, assume two landscapes with equal land area and area in private forest land have an average parcel size of 15 hectares, with 90% of the area in one landscape containing private forest parcels less than 16.19 hectares in size (the threshold value used in this case) while only 20% of the other landscape's private forest land resides in parcels less than 16.19 hectares. Adjusting the average parcel size of each township to account for the proportion of forest land in parcels less than 16.19 hectares produces parcelization metrics that differ by nearly five-fold (e.g., 0.06 for the landscape with 90% of its private forest landscape in parcels less than 16.19 hectares vs. 0.013 for the landscape where only 20% of private forested land is in parcels less than 16.19 hectares).

4. Results

To illustrate the influence that the choice of parcelization metric has on characterizing a landscape, we calculated values of the four parcelization metrics for each of the 410 townships within the study area. Table 1 presents the descriptive statistics for each metric. It is important to note that while smaller Mean values indicate a higher level of parcelization, we expect increasing parcelization to be associated with larger Gini, Entropy, and Adjusted Mean values.

Table 2
Parcelization metrics for three townships within the study area with nearly identical mean parcel size (Mean), but different Adjusted Mean, Gini, and Entropy values. Numbers in () are threshold values (ha) used to calculate Adjusted Mean values.

Township	Mean	Adjusted Mean	Gini	Entropy
6a	16	112 (4) 411 (16) 547 (32.4)	0.63	5.8
6b	16	234 (4) 554 (16) 699 (32.4)	0.79	4.9
6c	15	4 (4) 7 (16) 34 (32.4)	0.64	2.8

Also note the dispersion of each metric varies considerably. Within the study area, the range of the Gini coefficient is less than one (by its formulation), while there is over a 4400-unit difference between the minimum and maximum Mean values.

Fig. 4 illustrates the relationship among each of the metrics. This figure indicates the Gini, Entropy, and Mean metrics exhibit modest to no discernable patterns of association to each other, whereas the Mean and Adjusted Mean values are orthogonal. The relationships among the Gini, Entropy, and Adjusted Mean metrics appear to be nonlinearly correlated, with only the latter two showing a strong nonlinear correlation. In sum, Fig. 4 illustrates that each of the four metrics uses a unique combination of landscape attributes to characterize the degree to which forest parcelization exists.

Fig. 5 depicts patterns of forest parcelization across the six-county study area using the four metrics. Each map displays the township values for the parcelization metric in quantiles, with darker shading corresponding to what we posit to be a higher level of parcelization within the landscape. All four maps suggest the most parcelized forested landscapes are located in the southern portion of the study area, while the least parcelized landscapes are in the north. Yet beyond these generalizations, each metric describes subtly to markedly different patterns of parcelization. For example, use of the Gini coefficient would suggest substantial parcelization heterogeneity in the northeast portion of the study area, whereas the other three metrics describe this as an area with a consistently low level of parcelization. Also in contrast to the Mean, the other three metrics suggest a different picture of parcelization in the southern part of the study area. Specifically, the map of the Gini coefficient values shows the most highly parcelized landscapes are concentrated in the mid latitude, far eastern part of the study area. Yet the other three maps show the most parcelized landscapes (townships) occurring in the southwestern portion of the study area. Even the maps depicting mean parcel size, Entropy, and the Adjusted Mean metrics, while illustrating similar overall parcelization patterns, show distinct arrangements. Such differentiation is most evident in those townships where the private forest land base is not at either extreme of the distribution.

5. Discussion

A primary motivation for this study is to identify a metric(s) that better capture the range of parcelization conditions than mean parcel size. To illustrate, Fig. 6 and Table 2 present three townships within the study area having essentially the same average private forest land parcel size, but different Gini, Entropy, and Adjusted Mean scores. Each township exhibits a different picture of the extent to which its private forest land base has been parcelized. The township illustrated in Fig. 6a has approximately one-third its land area in private forest ownership, with relative uniformity in the size of individual parcels. One might conclude that with very few large private forest tracts, the private forest landscape in this

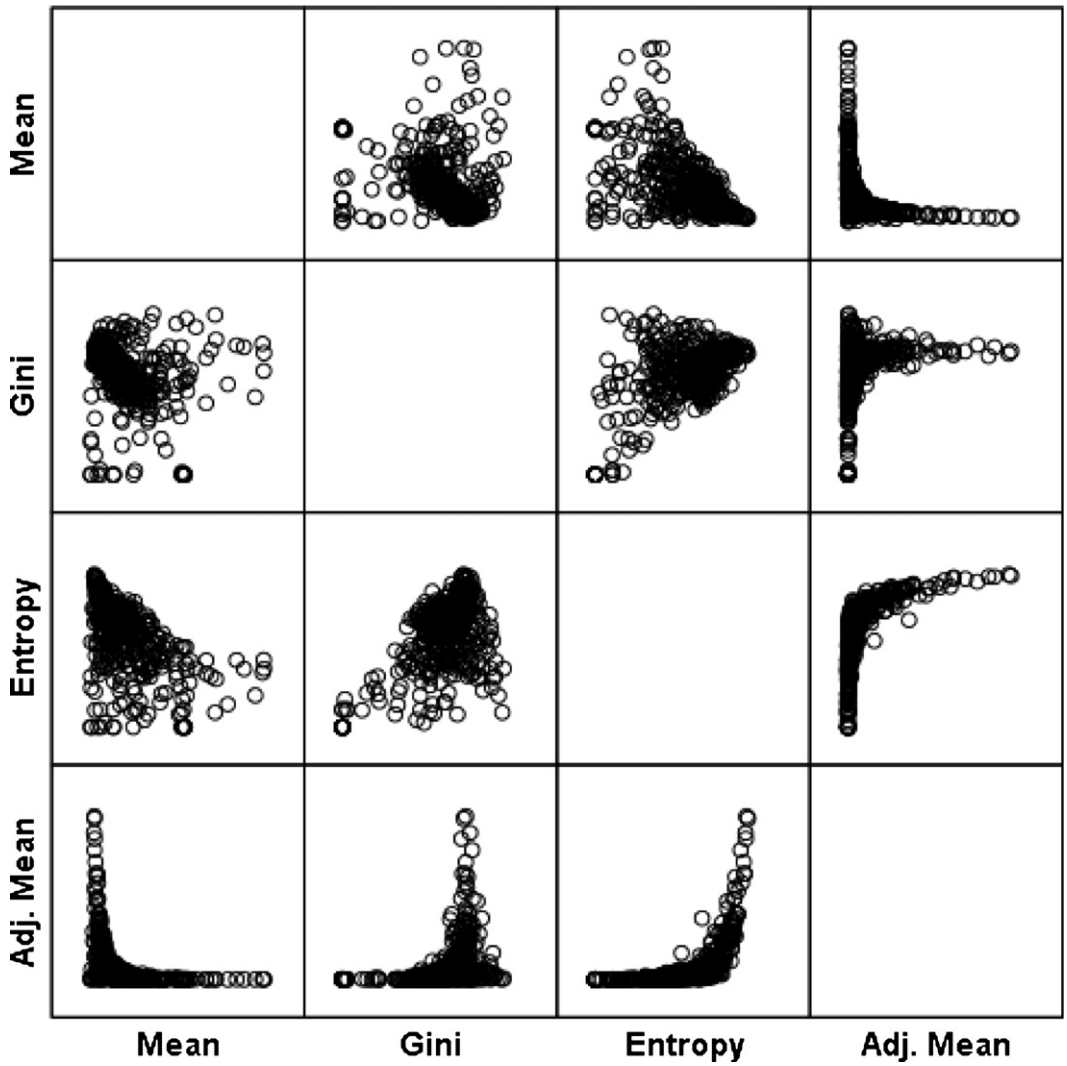

Fig. 4. Scatterplots of four parcelization metrics: mean parcel size, Gini coefficient, entropy, and new (adjusted mean) parcelization metric.

township is highly parcelized. The township in Fig. 6b, with most of its land area in private forest land, contains substantial variability in the size of individual parcels. Two of the private forest parcels are extremely large, collectively accounting for nearly two-thirds of the private forest land within the township. The remaining private forest parcels are relatively small to very small tracts. Characterizing the extent of parcelization in this landscape is not intuitive. The township depicted in Fig. 6c contains very little private forest land. Because large contiguous areas of private forest land do not exist in this township, one might conclude little parcelization has occurred.

Beyond highlighting the deficiencies of using mean parcel size, the above examples illustrate how the choice of parcelization metric influences how one assesses the degree to which a landscape is parcelized. The Gini coefficient, for example, reflects the dispersion of individual parcel sizes across the private land base, but it cannot discern whether the bulk of the parcels are either "large" or "small." Similarly, the Entropy index metric measures the degree of parcel size heterogeneity, but can take on the same value for quite different parcel size distributions. For Mean parcel size, the average size of forested parcels within the landscape is the indicator of parcelization. For the Adjusted Mean indicator, the degree to which a landscape is parcelized is measured by the proportion of the private forested landscape in parcels below a size threshold relative to the total number of private forest parcels in the landscape.

We seek a single-value parameter that assesses the degree of parcelization in a forest landscape. Of the four metrics examined here, two capture notions of many small parcels (Mean and Adjusted Mean), and two capture the idea of inequality or heterogeneity among parcel sizes (Gini and Entropy). Unfortunately, the behavior of these four metrics across a range of real landscapes suggests some difficulties. Yet, Fig. 4 suggests Entropy and Adjusted Mean measures are strongly correlated. We therefore examine Entropy and Adjusted Mean in greater detail across a range of parcelization patterns, scales, and administrative boundaries.

5.1. Choice of metric

Fig. 7 illustrates four townships in the study area. Fig. 7a depicts a highly parcelized township with extremely high Entropy and Adjusted Mean values, while Fig. 7b has largely unfragmented private forest land ownership pattern with extremely low Entropy and Adjusted Mean values (Table 3 contains the values of the four metrics, and Fig. 8 shows the frequency distribution of parcel size within each). Each metric seems to "work" fairly well near the extremes of its range: we think few would argue that Fig. 7a, containing very high Entropy and Adjusted Mean values, is not parcelized. Similarly, the township in Fig. 7b has very low values for both metrics and illustrates a largely intact private forest landscape.

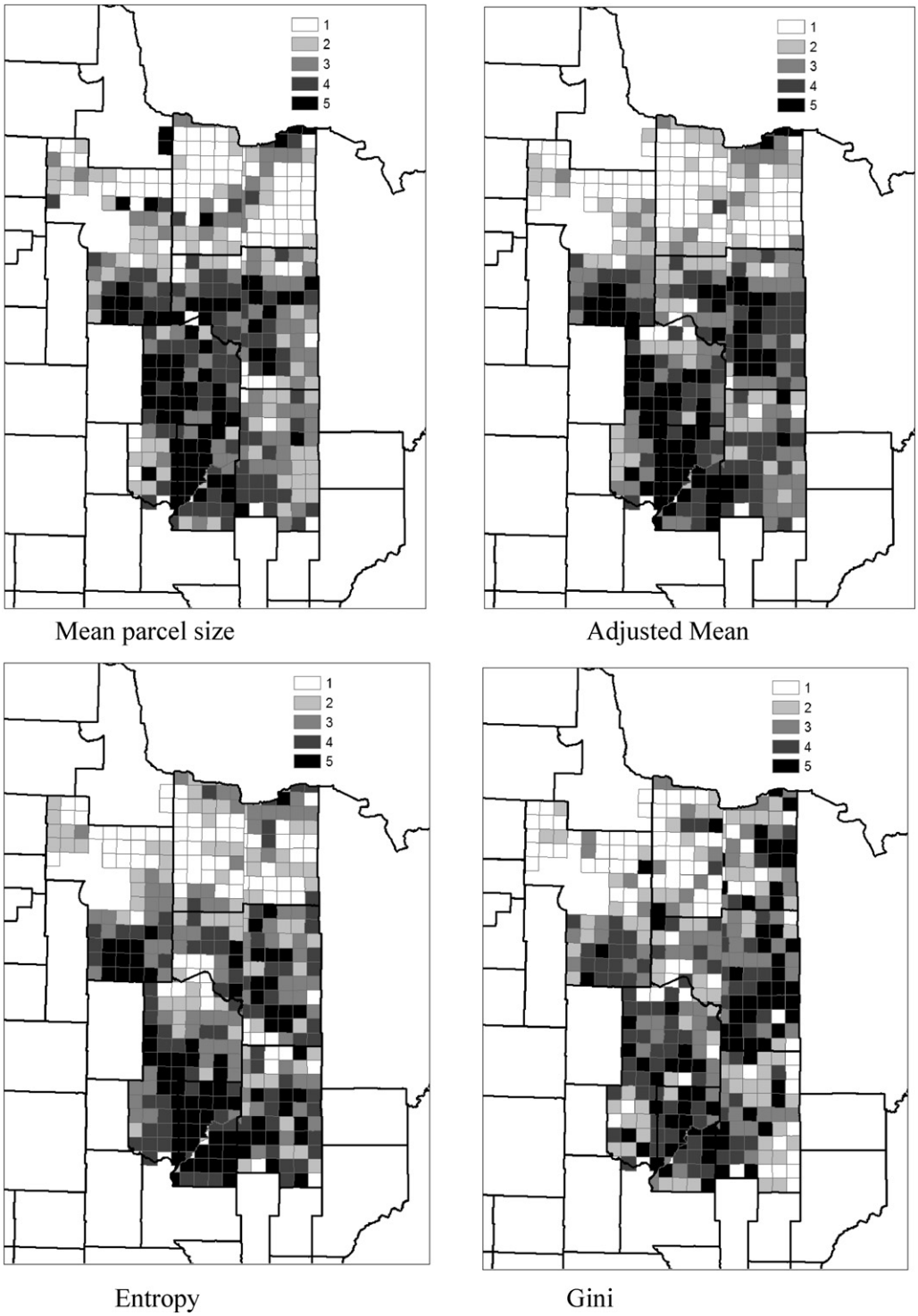

Fig. 5. Patterns of parcelization across the six county study area using the four metrics evaluated. Shading gradients represent the quantile distribution of metric values, with darker shading indicative of higher degrees of parcelization.

Table 3
Parcelization metrics for four townships mapped in Fig. 7.

Map	Mean	Adjusted Mean	Gini	Entropy
7a	15	731	0.74	6.2
7b	180	4	0.83	3.0
7c	65	46	0.54	5.7
7d	31	240	0.85	4.1

However, when the two metrics diverge in terms of their relative ranking (e.g., a low Entropy but midrange Adjusted Mean score), determining whether a landscape is parcelized is not intuitive. For example, Fig. 7c has a high Adjusted Mean score (i.e., within the upper 20% of all such values for the study area), but a midrange Entropy value (in the upper 40% of all such values). Similarly, Fig. 7d has a high Adjusted Mean value, but contains a midrange Entropy score. In both cases, characterizing whether the private forest landscape in the township has been parcelized

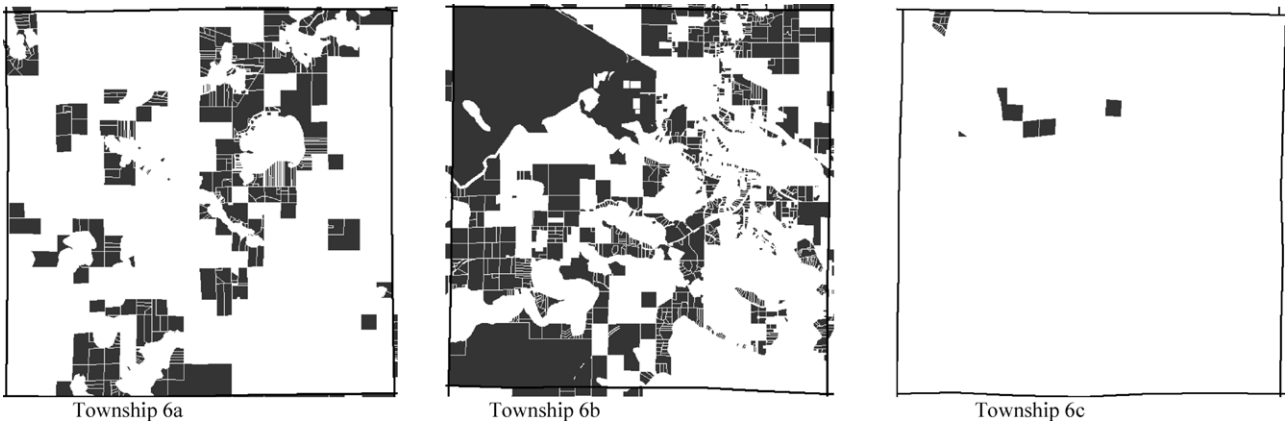

Fig. 6. Three townships within the study area with nearly identical mean parcel size, but different Adjusted Mean, Gini, and Entropy values. Note the dark areas are private forest land, with the remaining area public forest or non-forest land.

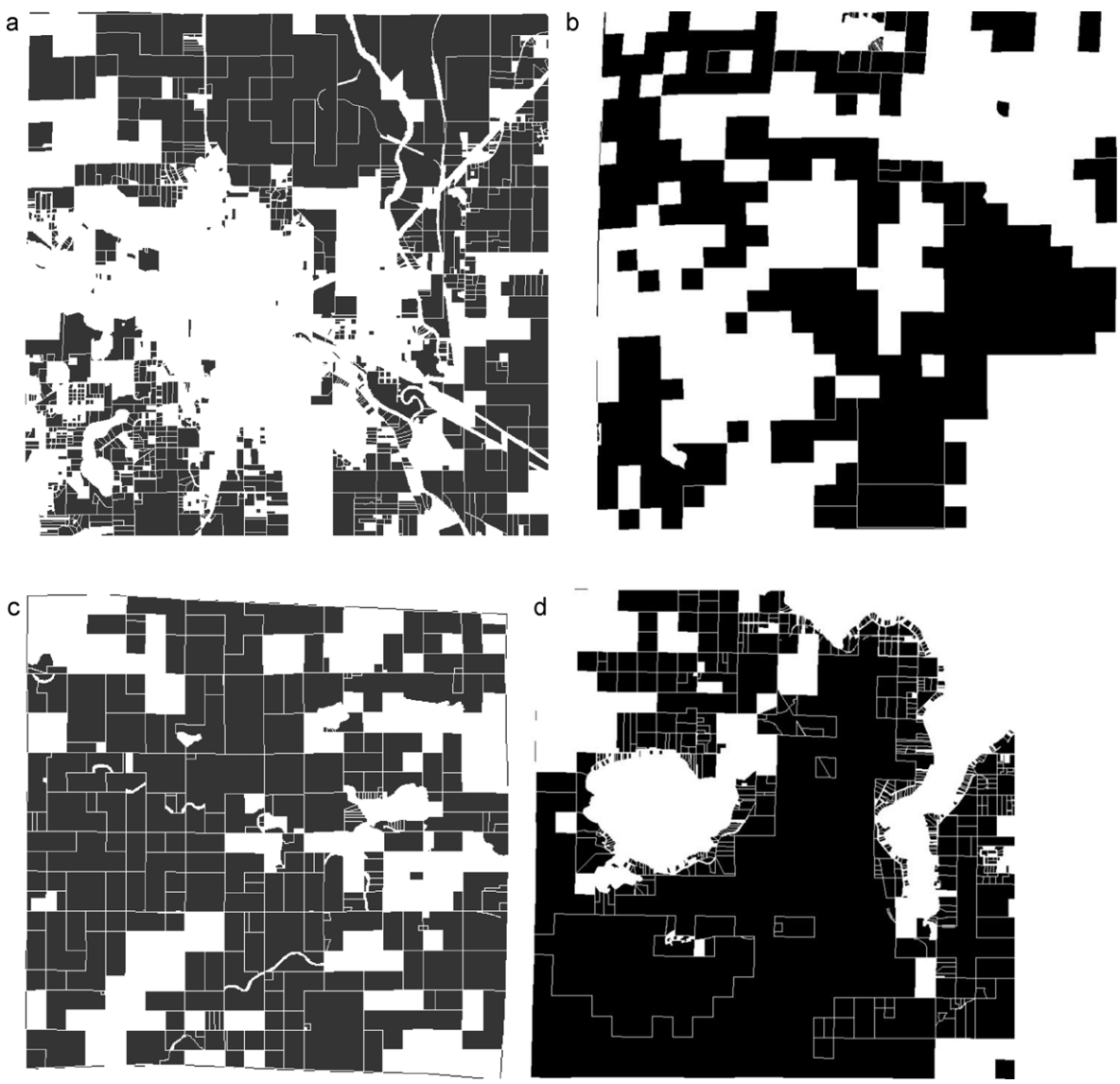

Fig. 7. Selected townships within the study area and associated Entropy and Adjusted Mean values.

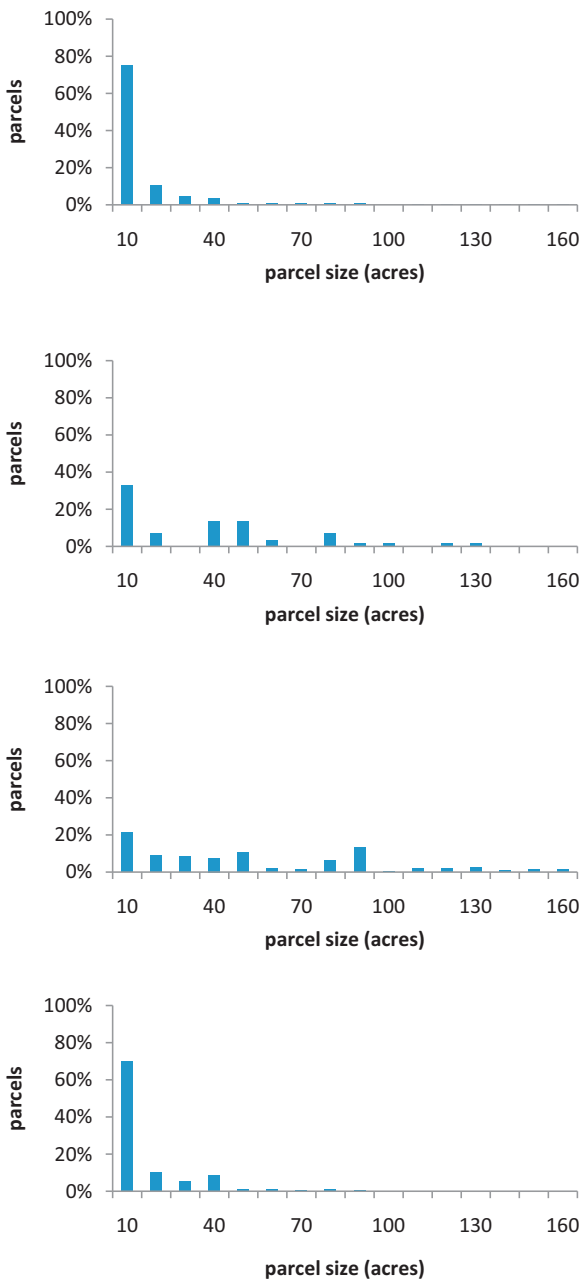

Fig. 8. Frequency distributions for sub-160 acre parcels in the four townships mapped in Fig. 7. Distributions are presented in order from a–d.

becomes indeterminate. . . some would say "yes" while others "no." We conclude that at the mid ranges of the Entropy and Adjusted Mean values, the choice of metric is not obvious or trivial, and can lead to considerably different characterizations of a parcelized landscape.

5.2. Choice of scale

The scale used to analyze a landscape also influences the interpretation of parcelization metrics. In this section, we demonstrate our points by focusing on Adjusted Mean. Fig. 9 is the same township shown in Fig. 7d, with Adjusted Mean scores (using study area quantiles of this value) assigned to each section (a 259 hectare unit of land measurement in the U.S.). Fig. 10 extends the scope to an entire county in the study area, using study area quantiles for Adjusted Mean values that are township-based (Fig. 10a) and

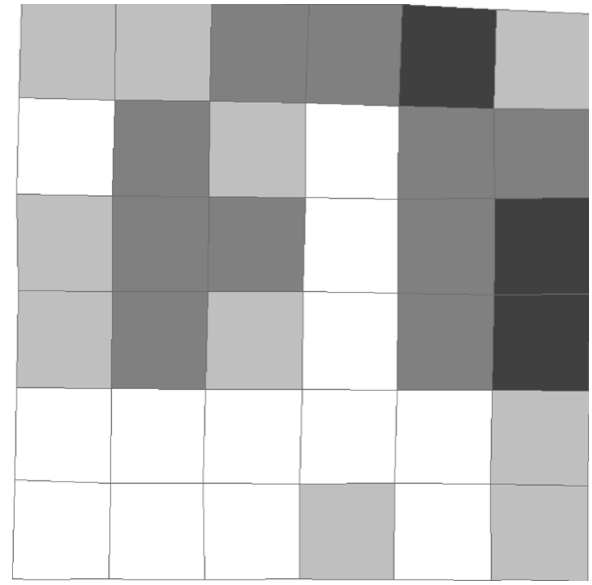

Fig. 9. Township shown in Fig. 7d depicting Adjusted Mean scores for each section using study area quantiles. Darker sections represent a greater level of parcelization.

section-based (Fig. 10b) averages. Each illustrates very different patterns of parcelization within the same landscape according to the scale used to calculate the parcelization metric values. Table 4 shows how the calculated values of the four parcelization metrics change, depending upon whether the unit of analysis (i.e., the landscape) is a section (259 hectares), township (9324 hectares), or county (ranging from 157,150 to 701,282 hectares). The table illustrates that the scale decision, while a matter of protocol, has large implications on the values of parcelization metrics. Fine scale analysis produces greater sensitivity to changes in ownership patterns, but increases the number of parcels within the landscape, because of the way in which our protocol combines adjacent parcels into single ownership units. Coarse scale analysis, in contrast, is able to more accurately define private forest landscapes, but does so at the expense of ownership pattern detail.

5.3. Choice of threshold parcel size

Determining that a forest landscape has become parcelized first requires a decision about the minimum size of individual parcels below which important economic, ecological, and social functions associated with intact forests are substantially compromised. It also requires a decision about when the number of parcels (area) below this threshold becomes great enough, as well as their juxtaposition across the landscape, such that the resulting ownership patterns will impair landscape functions. Little is available in the literature to guide such decisions. The subjectivity of these decisions suggests that no rules or theories exist for defining a parcelized landscape. Rather, there likely exists a gradient within which many would agree a landscape has become parcelized. The majority of forested landscapes we examined did not contain extreme ownership pattern conditions, making a characterization of whether the landscape has been parcelized difficult. Table 2 contains three different Adjusted Mean values using 4, 16, and 32.4 ha thresholds (10, 40, 80 acres) to illustrate how the values of the Adjusted Mean metric vary when different area thresholds are used.

5.4. Defining a parcelized landscape

If one assumes that each of the examined metrics captures something about the degree of parcelization in a landscape, the fact

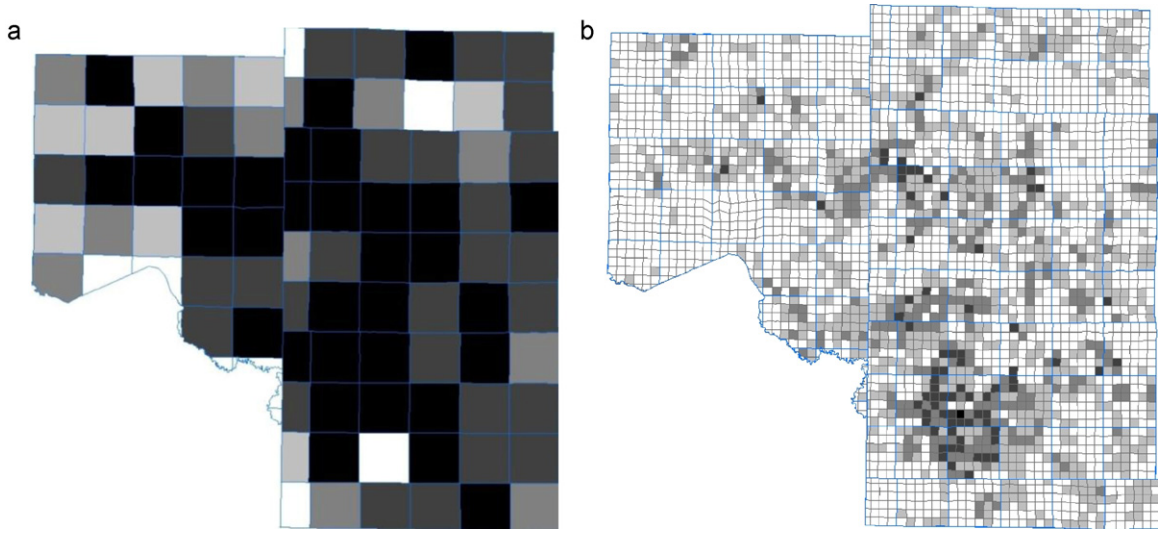

Fig. 10. Adjusted Mean scores for Itasca County. (a) Township-level Adjusted Mean scores using study area quantiles for that metric. (b) Section-level Adjusted Mean scores using study area quantiles for that metric.

Table 4
County, township, and section-average parcelization metric values for Itasca County.

Geographic Unit of Analysis	Mean Parcel Size	Adjusted Mean	Gini Coefficient	Entropy	Number of Forest Parcels[a]
County	20	5152	0.80	7.4	28,676
Townships	31	114	0.64	4.5	34,112
Sections	34	9	0.37	1.9	39,702

[a]The 11,000+ difference in the number of parcels when the unit of analysis is the section (39,702 parcels) and county (28,676 parcels) can be attributed to the need to treat individual parcels straddling political (e.g., section) boundaries as two (or more) individual parcels, each assigned to a separate geographic unit.

that each produces dramatically different scoring patterns across a range of landscapes suggests each metric reflects certain unique attributes of a landscape that might be key indicators of fragmented forest ownership. We suspect that that the choice of the "appropriate" metric will depend upon what specific aspects of parcelization are considered important by various analysts. For recreation planners and wildlife ecologists, it might be the private forest land area within a landscape that is held in large, contiguous ownership blocks. If protecting water quality is of primary interest, a metric that accounts for the number of parcels adjacent to lakes and rivers might be preferred. Foresters might favor a metric that reflects the amount of forest land within a landscape that meets minimum size and accessibility criteria. A parcelization metric that fails to capture the important indices of fragmented forest land ownership (as viewed by the policymaker, planner, or land manager) can result in an inaccurate assessment of a parcelized landscape and possibly the selection of inappropriate policy tools for mitigating the effects of parcelization.

Our analysis also suggests that before a meaningful definition of forest parcelization can be developed, a range of metrics and thresholds needs to be examined to identify which ones are relevant and meaningful with respect to impacts on social or ecological processes of interest. This is a significant gap in the parcelization literature. Needed is information on specific physical and spatial features of forest ownership within a landscape that are considered to be key indices of parcelization and its consequences. For example, Vickery et al. (2009) determined the probability of sustained yield management approaches 100% for a forested parcel is at least 30 acres. These features could be discerned through an exercise whereby various landscapes are ranked by natural resource managers according to the degree to which they are considered parcelized. Others (e.g., Vickery et al., 2009; Wear, Liu, Foreman, & Sheffield, 1999) have used similar methodologies to obtain opinions from natural resource managers, which could be applied to determine relevant parcelization metrics and thresholds.

Once the physical and spatial characteristics associated with this landscape are identified and quantified, appropriate metrics of parcelization that capture these important features of a parcelized landscape can then be developed. Where possible, evaluating changes in these metrics over time (e.g. Kennedy & McFarlane, 2009; Mundell et al., 2010) provides additional information and perspective regarding changing ownership patterns within the landscape.

6. Conclusions

The choice of metric to describe the fragmentation of forest land ownership – parcelization – within a landscape is not trivial and has implications as to how data describing intensity and extent of parcelization can be interpreted. Numerous metrics exist or can be developed that characterize the extent to which a forested landscape has been parcelized, each emphasizing specific physical features, spatial dimensions, and/or ownership patterns. Our analysis of four metrics applied to our specific landscape suggests each one describes parcelization differently. Each captures different aspects of ownership patterns within a landscape and is a function of the defined scale and threshold measures. Yet without any standardized ranking of parcelized landscapes, we are unable to gauge the actual performance of our metrics.

Another aspect of our study that distinguishes it from previous research is our investigation of analysis scale. We compare

findings using multiple parcelization metrics over the following three analysis scales: sections (defined as 259 hectares), survey townships (roughly 9324 hectares), and counties (large, sub-state units of government) to illustrate the influence that analysis scale also has on describing a parcelized landscape. Through empirical analysis, our research demonstrates that the choice of metric, the scale of analysis, and administrative unit can influence the degree to which a landscape is considered parcelized.

A critical need is for resource managers to rank landscapes as to their degree of parcelization. While we have demonstrated that it is possible to score a landscape using any number of quantitative methods, the translation of how any particular landscape score relates to a degree of parcelization is missing and must ultimately be supplied by those who can relate a landscape pattern to potential adverse resource impacts. Parcelization is not a one-size-fits-all concept that can easily or unequivocally be captured by any one metric across all landscape scenarios. We further argue that a landscape's parcelization ranking will likely differ depending upon which resource concern is considered when characterizing the landscape; thus, we argue that there is not likely to be a universal, single-best parcelization metric. For this reason, we cannot conclude that any one of the four metrics we examined is either the most appropriate or inappropriate for use in characterizing a parcelized landscape. Parcelization is a multi-dimensional phenomenon that will likely require a multi-dimensional metric.

We offer these general comments to help in motivating discussions about what is a useful or appropriate parcelization metric. From our analysis, we conclude Adjusted Mean is the most meaningful measure of forest land parcelization of the four we evaluated. Many of the adverse ecological, recreational, and economic impacts associated with a parcelized forest landscape are a function of individual parcel size, not necessarily the distribution of parcel size classes. Moreover, the functionality of a forested landscape to provide these ecological, recreational, and economic benefits is dependent on the aerial extent of small parcels within a landscape, which is captured by the Adjusted Mean. We view the inability of individual Gini and Entropy values to describe a single, unique parcel size distribution within a landscape to be an important limitation.

Yet we point out an important limitation with the Adjusted Mean metric, namely the arbitrary assignment of the parcel size threshold and the aerial extent of the landscape. Such limitations can be largely overcome by computing multiple metrics that reflect different threshold parcel size classes and landscape scales. By comparing Adjusted Mean metric values across a range of parcel thresholds and landscape scales, resource analysts and managers can better determine key "break points" when large changes in parcelization are occurring.

A final conclusion has to do with the need for science to inform resource analysts and managers about the implications of forest land parcelization. The appropriateness of specific metric parameters (e.g., threshold acreage) is dependent on knowing when important forest benefits and functions become impaired as a result of an increasingly parcelized landscape. Science has an important role in identifying the nature and magnitude of these impairments across a gradient of parcelized landscapes. With such information, analysts would be able to develop parcelization metrics that capture the most important physical features and spatial patterns of a forest landscape.

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