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Areas influenced by multiple edges and their implications in fragmented landscapes

Qinglin Li [a,*], Jiquan Chen [b], Bo Song [c], Jacob J. LaCroix [d], Mary K. Bresee [b], John A. Radmacher [b]

[a] Timberline Natural Resource Group Ltd., 1884 Spall Road #214, Kelowna, British Columbia V1Y 4R1, Canada
[b] Department of Environmental Sciences, The University of Toledo, MS 604, Toledo, OH 43606, USA
[c] Belle W. Baruch Institute of Coastal Ecology and Forest Science, Clemson University, P.O. Box 596, Georgetown, SC 29442, USA
[d] National Marine Fisheries Service, Auke Bay Laboratories, Juneau, AK 99801, USA

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Abstract

We introduced a new approach for delineating areas of multiple edge influence (AMEI) within a fragmented landscape using a geographic information system (GIS). AMEI was defined as the interface that is affected by more than two neighboring patch types. We decomposed AMEI into three components: $AMEI_1$, the area where one patch type meets a different patch type; $AMEI_2$, the area where one patch type meets two different patch types; $AMEI_3$, the area where one patch type meets three or more other different patch types. This approach provides a direct measure of the complexities of multiple edge effects that may occur at a spatial location, and also measures the amount of the affected area at the patch and landscape levels. Using the Chequamegon National Forest (CNF), USA, as a case study, we found that the total AMEI was approximately 48, 74, 86, and 92% of the landscape with depth of edge influence (DEI) at 30, 60, 90, and 120 m, respectively. The more complicated components of the area of multiple edge influence ($AMEI_2$ and $AMEI_3$) ranged from 5% (at 30 m DEI) to 60% (at 120 m DEI) of the studied landscape. Most empirical and modeling studies miss this additional edge complexity if they only consider a single edge structure. In general, $AMEI_1$ is greater than $AMEI_2$; $AMEI_2$ is greater than $AMEI_3$. Three indices – AMEI to patch area ratio (APAR), AMEI to patch edge area ratio (APEAR), and AMEI to landscape area ratio (ALAR) – were introduced to explain the relative importance of AMEI at the edge, patch, and landscape levels. This approach has the potential to improve model predictions and better inform us about ecological processes that are influenced by multiple edge effects at patch and landscape scales.

Keywords: Edge effects; Area of multiple edge influences (AMEI); Depth of edge influences (DEI); Fragmentation; Landscape analysis

1. Introduction

Edges and area-of-edge influence (AEI) are considered as the primary features of natural and fragmented landscapes (Franklin and Forman, 1987; Murcia, 1995; Harper et al., 2005a; Chen et al., 2006) because of their crucial ecological importance in driving ecosystem and landscape processes and, ultimately, on landscape functions (Laurance et al., 1998; Harrison and Bruna, 1999; Ries et al., 2004). Edge effects occur within the AEIs, which has been proposed to be a unique landscape element, structurally and functionally (Sanderson and Harris, 2000; Chen et al., 2006). While an increasing number of studies on various foci (e.g., edge structure, formation and dynamics during fragmentation, ecological consequences, methods for delineating edges and AEI, and united theories) has greatly enhanced our understanding of edges and their influences over the past two decades, we lack a fundamental understanding of the area that multiple edges influence—those AEIs influenced from more than one direction. Not only is our knowledge on how and to what degree multiple edges interact to influence ecosystem processes is limited, but how complex patch geometry and patch patterns determine the amount and distribution of the areas of multiple edge influence in a fragmented landscape also has not been examined thoroughly (Ries et al., 2004; Fletcher, 2005). Additionally, no method has been proposed for quantitatively delineating AMEIs at different spatial scales or for situations where the depth-of-edge influence (DEI) varies.

* Corresponding author. Tel.: +1 250 762 3191; fax: +1 250 762 3192.
E-mail address: geoliqinglin@yahoo.com (Q. Li).

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Edges and edge influences have been studied mostly with simple cases where two contrasting patches meet in both empirical and theoretical research. It is common for researchers to purposely locate their study sites in the middle section of an edge to avoid complicating factors from other adjacent patches (Haefner et al., 1991; Chen et al., 1992; Harper et al., 2005b), or simply delineate AEIs by presuming a fixed DEI in landscape structural analysis (Chen et al., 1995; Riitters et al., 1995; McGarigal and Marks, 2002; Bresee et al., 2004). Yet, recent studies have found that multiple edges can affect not only the magnitude, but also the extent of ecological processes (Zheng and Chen, 2000; Fletcher, 2005; Euskirchen et al., 2006). In a recent study, Ries et al. (2004) commented that no empirical study has measured how the convergence of multiple patch type affects AEI and its ecological processes. Fletcher (2005) reported that the complexity of multiple edge junctions was very important in extrapolating edge effects on bird distribution in a fragmented landscape. Clearly, an essential step before evaluating multiple edge effects requires determining where and to what degree the AMEIs exist on the landscape.

We examined AMEIs and their distribution in this study using classified land coverage within a geographic information system (GIS). Our specific objectives were to: (1) propose a new approach to delineate AMEIs on the landscape, (2) determine the AMEIs with different values for depths of edge influence, and (3) examine the variation of AMEIs at patch and landscape levels based on the new quantitative measures (i.e., AMEI to patch area ratio, AMEI to total AEI ratio, and AMEI to landscape area ratio). Each quantitative measure provides a unique insight to AMEI distribution and their importance in the overall landscape structure. AMEIs can also support future location-specific studies in assessing landscape pattern–process relationships.

2. Methods

2.1. Definitions and model structure

AMEI, in this study, was defined as the interface affected by one or more neighboring patch types and was decomposed into three components:

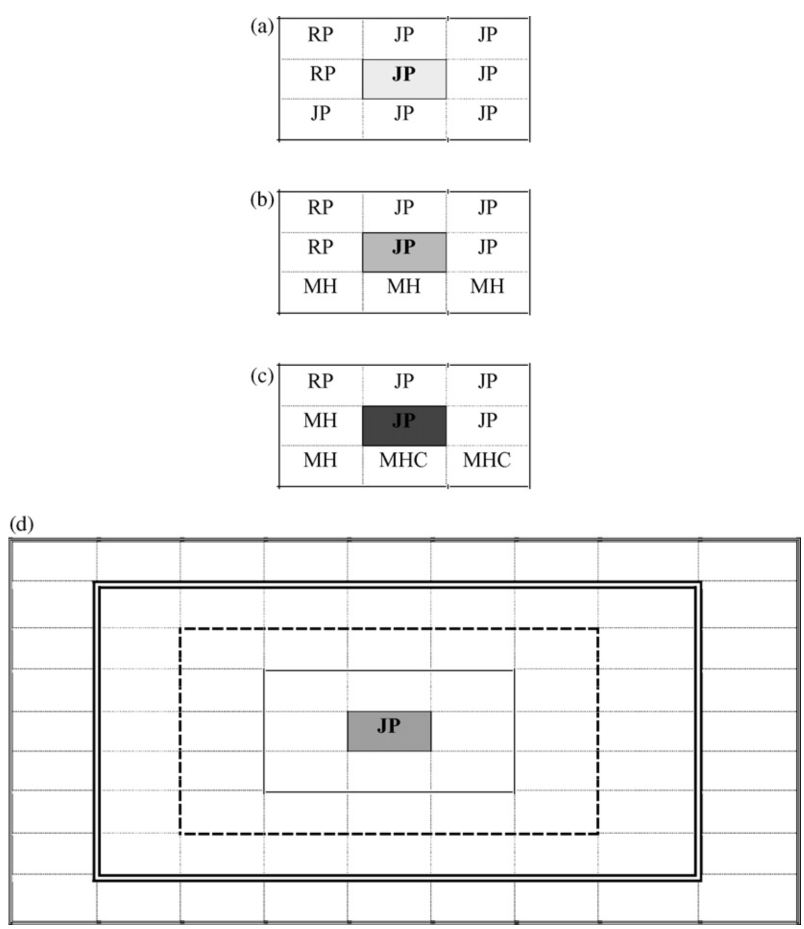

Fig. 1. (a–c) illustrate AMEI$_i$ calculation within a 3 × 3 moving window for 30 m depth of edge influence (DEI): (a) the area of multiple edge influence (AMEI) at the first level, which has a jack pine (JP) patch type affected by one different neighboring patch type (red pine, RP); (b) AMEI at the second level, which is a JP affected by two different neighboring patches (RP and mixed hardwood, MH); (c) AMEI at the third level, which is a JP affected by three (RP, MH, and mixed hardwood/conifer, MHC) or more different neighboring patches; (d) The 5 × 5, 7 × 7, and 9 × 9 moving window was used to calculate 60, 90, and 120 m DEI followed the 3 × 3 moving window conceptual design. The capital letters stand for patches, dark grey is the center pixel, and light grey represents the neighboring patches. The solid line is a 3 × 3-moving window, dashed line is a 5 × 5-moving window, doubled line is a 7 × 7-moving window, and triple line is a 9 × 9-moving window.

- $AMEI_1$, the area where one patch type meets another;
- $AMEI_2$, the area where one patch type meets two different patch types;
- $AMEI_3$, the area where one patch type meets three or more different patch types.

The $AMEI_i$ ($i = 1$, 2, or 3) model was constructed by identifying the spatial location of AMEI within a heterogeneous landscape. These three components are independent and can be summed to interpret the total area impacted by edges as a simple core-area model (McGarigal and Marks, 2002). However, the complexity of AMEI explicitly identified by this model is more useful in explaining ecosystem processes (i.e., forest fires spread) occurring within multiple edges. The computational steps of the AMEI model consist of different sizes of moving windows (i.e., 3 × 3, 5 × 5, 7 × 7, and 9 × 9) to quantify different depths of edge influence (i.e., 30, 60, 90, and 120 m). For example, within a 3 × 3-moving window, for any given pixel in the center of the window, attributes of each of its neighboring pixels were examined and analyzed. If only one new patch surrounded the center pixel patch type, the center pixel was classified as $AMEI_1$ (Fig. 1a). If there were two patch types, the center pixel was classified as $AMEI_2$ (Fig. 1b). For three or more different patch types, the center pixel was classified as $AMEI_3$ (Fig. 1c). Lastly, if the center pixel was the same as its eight neighboring pixels, it remained unchanged (or the core area). The same concept was used to calculate 60 m, 90 m, and 120 m of DEI by using 5 × 5, 7 × 7, and 9 × 9-moving windows, respectively (Fig. 1d).

2.2. Study area

The study area was located at the Washburn Ranger District of the Chequamegon National Forest (CNF) in northern Wisconsin, USA (46°30′–66°45′N, 91°02′–91°22′W). The total landscape area was 39,272 ha, with six dominant patch types including mixed hardwood (MH, over 16 years old), mixed hardwood/conifer (MHC, over 16 years old), non-forest bare ground (NFBG, 0–5 years old), regenerating forests/shrubs (RFS, 6–15 years old), jack pine (JP, over 16 years old), and red pine (RP, over 16 years old; Bresee et al., 2004). The area of each patch type was 9556 ha (RFS), 10,606 ha (MH), 9815 ha (MHC), 3409 ha (NFBG), 1266 ha (JP), 4471 ha (RP), and 149 ha of water (not included in the analysis). The primary conservation effort was the pine-barrens region located in the southwest corner of the CNF and was dominated by regenerating forests/shrubs and non-forest bare ground patch types. These patch types were direct results of the CNF management activities (i.e., prescribed burning, road construction, and harvesting). Mixed hardwood was the most contiguous patch type in the landscape, whereas, jack pine was the most fragmented. Fragmentation of jack pine occurred mostly from insect and disease outbreaks and harvesting practices (Adams et al., 1995; Radeloff et al., 1999, 2000). Mixed hardwood/conifer was typically a transition cover type between mixed hardwood, jack pine, and red pine, but fairly continuous. Red pine, the dominant commercial species, was separated into large and small management blocks in the northeastern portion of the CNF (Vora, 1993).

We used a classified Landsat 7 ETM + image for 2001 (12 June; Bresee et al., 2004). Pre-processing was performed to dissolve isolated pixels. This classified image was the input for the AMEI model. The 30–120 m DEIs were the common distances found by researchers to have significant edge effects on many species (Euskirchen et al., 2001). Furthermore, the DEI of abiotic or biotic elements, such as solar radiation, wind velocities, or lichen distributions, can extend tens to hundreds of meters into a patch depending on edge contrast (Chen et al., 1996; Keyser et al., 1998). The DEI may also differ depending on the edge developmental stage, for example, sealing, softening, or expanding over time (Harper et al., 2005b).

2.3. Data analyses

We calculated the amount of $AMEI_1$ as the percentage of the area of each neighboring patch to the area of the main patch type at different DEIs, which reflected the complexity of $AMEI_1$ in the landscape and their relative importance to the dominant patch types of the landscape. AMEI to patch area ratio (APAR) is the ratio of the total $AMEI_i$ ($i = 1$, 2, or 3) at each level to the area of the main patch,

$$\mathrm{APAR}_i = \frac{\sum_{j=1}^{n-1} \mathrm{AMEI}_i}{S_j} \times 100\% \tag{1}$$

where j ($j = 1, 2, 3, \ldots, n$) is the number of neighboring patches, i ($i = 1$, 2, or 3) the AMEI component, and S is the area of the main patch. APAR is a measure of the effects of each AMEI component to the main patch. Higher $APAR_i$ means the main patch received more effects from that AMEI component.

AMEI to patch edge area ratio (APEAR) is the ratio of the total AMEI of each component out of the total amount of edge per patch,

$$\mathrm{APEAR}_i = \frac{\sum_{j=1}^{n-1} \mathrm{AMEI}_i}{\sum_{i=1}^{3} \mathrm{AMEI}_i} \times 100\% \tag{2}$$

where i and j are the same as in Eq. (1). APEAR is a measure of edge's relative contribution to the total edge area of the dominant patch type. Higher $APEAR_i$ refers to a greater importance of the given AMEI type to the total edge effect for the dominant patch type.

AMEI to landscape area ratio (ALAR) is the percentage of the total AMEI of each component to the total area of the whole landscape,

$$\mathrm{ALAR}_i = \frac{\sum_{j=1}^{n-1} \mathrm{AMEI}_i}{\sum_{j=1}^{n} S_j} \times 100\% \tag{3}$$

where i and j are the same as in Eq. (1). ALAR is a measure of the relative importance of each AMEI at each dominant patch type to the total landscape. Higher $ALAR_i$ refers to a stronger effect of the AMEI in the landscape.

3. Results

Total AMEI ranged from 48 to 92% of the landscape as the DEI was set from 30 to 120 m. Total amount of AMEI and $AMEI_i$ nonlinearly increased with increasing DEI values. $AMEI_1$ increased from 42% at 30 m DEI to 50% at 60 m DEI, and then decreased to 33% at 120 m DEI. The $AMEI_2$ and $AMEI_3$ components increased with DEI, but were nonparallel to the changes in $AMEI_1$ (Figs. 2 and 3).

The effect of a patch on its neighbors is not equal to the receptive effects from neighbors regardless of DEI (Table 1). For example, 13% of regenerating forests/shrubs patch type was affected by non-forest bare ground patch type, while 31% of non-forest bare ground patch type was affected by regenerated forests/shrubs patch type at 30 m DEI. Using the percentage of any neighboring patch type as a measure of its relative importance to its main patch type, we found that non-forest bare ground contributed 12% to the edge area of the regenerating forests/shrubs main patch type at 30 m DEI, while it contributed 2% to the AEI of the mixed hardwood/conifer main patch type. It also seemed that any given main patch type will have a reciprocal relationship with its largest neighboring patch. When the largest neighboring patch is considered as the main patch by the delineating method, these two patches will have the greatest affect on each other regardless of DEI, except in the case of Red Pine. Therefore, at a given location the two largest touching patches form a reciprocal pair on the landscape. Lastly, the total percentage of $AMEI_1$ of each main patch type reached its

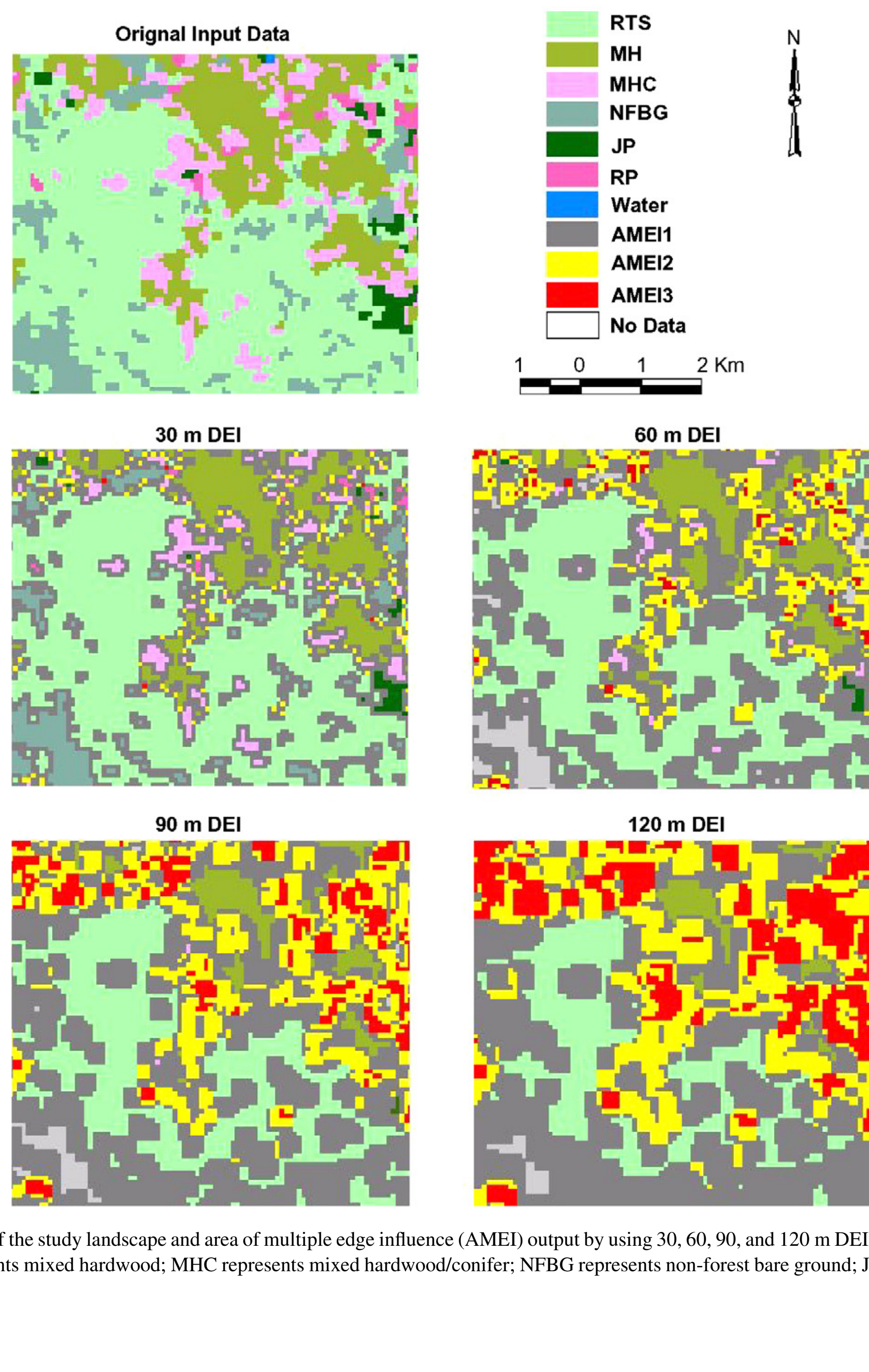

Fig. 2. The thematic map of the study landscape and area of multiple edge influence (AMEI) output by using 30, 60, 90, and 120 m DEI. RFS represents regeneration forests/shrubs; MH represents mixed hardwood; MHC represents mixed hardwood/conifer; NFBG represents non-forest bare ground; JP is jack pine; RP is red pine.

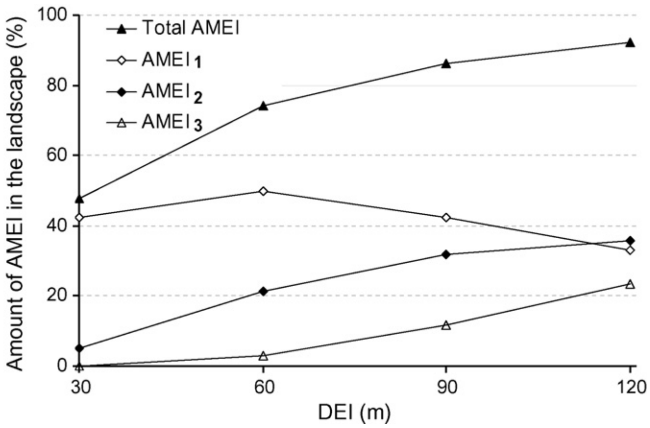

Fig. 3. The percentage of the total and each level of the area of multiple edge influence ($AMEI_i$) to the total area of the landscape with different depths of edge influence (DEI) ranging from 30 to 120 m at the Chequamegon National Forest (CNF), WI, USA. The solid triangle represents total AMEI, open diamond $AMEI_1$, solid diamond $AMEI_2$, and open triangle $AMEI_3$.

maximum at 60 m DEI except for the main patch type of jack pine (30 m; Fig. 3 and Table 1).

The first component of the area of multiple edge influence (AMEI) to the patch area ratio ($APAR_1$) had the largest percentage values for all main patch types at 60 m DEI except for in the case of jack pine (30 m), while the second ($APAR_2$) and third ($APAR_3$) components increased as DEI increased from 30 to 120 m except for the jack pine patch type for $APAR_2$ (Table 2). The APAR values decreased in all patch types with the APAR complexity increasing at 30, 60, and 90 m DEI, except for jack pine (60 and 90 m). There was no consistent pattern for which component would have the largest APAR values at 120 m DEI. For example, among all six patch types, the three largest APAR values were found at the second component, two high APAR values at the first component, and one at the third component. The main patch type of jack pine had the highest $APAR_1$ (58%) at 30 m DEI, while the smallest $APAR_1$ (9%) at 120 m DEI (Table 2).

The first component of the AMEI to patch edge area ratio ($APEAR_1$) decreased at all patch types with DEI increasing from 30 to 120 m, while the $APEAR_2$ and $APEAR_3$ increased with increasing DEI in all patch types, except $APEAR_2$ at non-forest bare ground (90 m), red pine (90 m), and jack pine patch type (60 m; Table 3). The APEAR values decreased with its complexity increasing within 30, 60, and 90 m DEI for all patch types, except for the jack pine patch type (60 and 90 m). However, within 120 m DEI, the largest APEAR values appeared two times in $APEAR_1$, three times in $APEAR_2$, and one time in $APEAR_3$ (Table 3).

The relative contribution of $ALAR_2$ and $ALAR_3$ increased with DEI increasing from 30 to 120 m in all patch types but jack pine (Table 4). For example, the $ALAR_3$ at the main patch type of regenerating forests/shrubs had less than 0.1% contribution to the total landscape at 30 m DEI, but ≈6% contribution at 120 m DEI. In contrast, the $ALAR_1$ reached its maximum at 60 m DEI except for the jack pine patch type (30 m; Table 4).

In general, the AMEI to the patch area ratio (APAR), AMEI to the patch edge area ratio (APEAR), and AMEI to the landscape area ratio (ALAR) increased with DEI at the second and third components, but decreased at the first component (Fig. 4a–c). Furthermore, all the values in the first component within the same DEI were greater than that at the second component, which was higher than that at the third component (Fig. 4).

Table 1
The percentage of area of multiple edge influence ($AMEI_1$) to main patch area at the first level by main patch and neighboring patches with different depths of edge influence (DEI) ranging from 30 to 120 m

Main patch types	Neighboring patches	30 m (%)	60 m (%)	90 m (%)	120 m (%)
RFS	MH	7.07	8.14	5.70	3.46
	MHC	11.86	13.13	10.06	7.17
	NFBG	12.89	16.84	17.57	16.66
	JP	2.66	2.53	1.80	1.25
	RP	4.47	4.37	3.27	2.26
Total		38.97	45.02	38.41	30.80
MH	RFS	7.19	8.20	6.31	4.12
	MHC	23.73	36.41	37.57	34.16
	NFBG	1.77	2.07	1.75	1.16
	JP	0.86	0.92	0.68	0.55
	RP	1.63	1.81	1.39	0.88
Total		36.14	49.68	47.90	40.98
MHC	RFS	11.52	11.79	8.38	5.18
	MH	26.27	31.04	37.37	21.14
	NFBG	1.63	1.54	0.73	0.24
	JP	1.60	1.38	0.71	0.29
	RP	7.92	10.13	8.47	6.25
Total		49.29	56.21	45.87	33.17
NFBG	RFS	30.67	38.02	36.24	31.07
	MH	4.60	4.17	2.90	1.32
	MHC	5.96	3.96	2.26	0.87
	JP	2.30	1.80	1.11	0.46
	RP	3.91	3.15	1.97	0.77
Total		47.45	54.29	44.48	34.49
JP	RFS	14.88	10.43	5.73	2.70
	MH	6.00	3.17	1.54	0.51
	MHC	12.88	5.46	2.27	0.57
	NFBG	4.01	2.36	0.99	0.34
	RP	20.21	12.37	7.86	4.41
Total		58.15	38.21	18.39	8.53
RP	RFS	9.55	11.03	8.95	6.98
	MH	3.57	3.25	1.98	1.05
	MHC	18.38	21.85	18.65	14.08
	NFBG	2.74	3.31	2.26	1.35
	JP	5.83	6.49	4.58	2.68
Total		40.10	45.95	36.42	26.12

RFS stands for regenerating forests/shrubs, MH represents mixed hardwood, MHC is mixed hardwood/conifer, NFBG is non-forest bare ground, JP is jack pine, and RP is red pine.

4. Discussion

We defined and examined the areas of multiple edge influence (AMEIs) and their characteristics at edge, patch, and

Table 2
The area of multiple edge influence ($AMEI_i$[a]) to patch area ratio (APAR) at three $AMEI_i$ levels with different depths of edge influence (DEIs) ranging from 30 to 120 m by main patch types

Main patch types	$APAR_i$	30 m (%)	60 m (%)	90 m (%)	120 m (%)
RFS	$APAR_1$	38.97	45.02	38.41	30.80
	$APAR_2$	5.05	21.61	31.55	33.93
	$APAR_3$	0.12	3.74	11.97	23.64
MH	$APAR_1$	36.14	49.68	47.90	40.98
	$APAR_2$	3.63	15.25	26.70	34.02
	$APAR_3$	0.06	1.59	6.79	12.74
MHC	$APAR_1$	49.29	56.21	45.87	33.17
	$APAR_2$	4.88	23.00	35.50	40.64
	$APAR_3$	0.09	2.81	11.23	18.59
NFBG	$APAR_1$	47.45	54.29	44.48	34.49
	$APAR_2$	7.08	22.54	32.62	33.69
	$APAR_3$	0.20	3.25	14.37	28.13
JP	$APAR_1$	58.15	38.21	18.39	8.53
	$APAR_2$	14.20	44.33	43.75	32.97
	$APAR_3$	0.53	13.24	36.56	57.40
RP	$APAR_1$	40.10	45.95	36.42	26.12
	$APAR_2$	6.25	22.44	33.11	34.18
	$APAR_3$	0.18	3.30	15.18	30.11

See Table 1 for abbreviations.
[a] AMEI levels: 1, 2, or 3.

landscape levels by categorizing them into three components: $AMEI_1$, $AMEI_2$, and $AMEI_3$. These measures, along with three quantitative measures (i.e., APAR, APEAR, and ALAR) provided a breakdown of information on the complexities of edge effects at different scales. Although multiple edge effects arising from complex patch geometry are poorly understood, previous studies have suggested that they could have a significant influence on ecosystem processes and overall landscape function (Chen et al., 2006). Chen et al. (2006) determined that the maximum edge influence is often found at patch corners where impacts are from more than one edge. As another example, Fletcher (2005) concluded that double-edge plots significantly reduced the number of birds compared to single-edge plots. He also recommended that model simulations should consider multiple edge influences while testing the complexity of edge effects on bird distribution.

Table 3
The area of multiple edge influence ($AMEI_i$[a]) to patch edge area ratio (APEAR) at three $AMEI_i$ levels with different depth of edge influence (DEI) ranging from 30 to 120 m by main patch types

Main patch types	$APEAR_i$	30 m (%)	60 m (%)	90 m (%)	120 m (%)
RFS	$APEAR_1$	88.29	63.97	46.87	34.86
	$APEAR_2$	11.42	30.69	38.52	38.39
	$APEAR_3$	0.29	5.34	14.62	26.75
MH	$APEAR_1$	90.75	74.66	58.86	45.69
	$APEAR_2$	9.07	22.93	32.81	37.94
	$APEAR_3$	0.18	2.41	8.33	16.36
MHC	$APEAR_1$	90.83	68.55	49.55	34.33
	$APEAR_2$	8.98	28.03	38.34	42.05
	$APEAR_3$	0.19	3.41	12.10	23.62
NFBG	$APEAR_1$	86.69	67.80	48.63	35.82
	$APEAR_2$	12.94	28.14	35.67	34.98
	$APEAR_3$	0.37	4.06	15.71	29.20
JP	$APEAR_1$	79.82	39.89	18.64	8.63
	$APEAR_2$	19.47	46.27	44.33	33.32
	$APEAR_3$	0.70	13.83	37.03	58.05
RP	$APEAR_1$	86.18	64.11	42.99	28.88
	$APEAR_2$	13.46	31.28	39.09	37.81
	$APEAR_3$	0.36	4.61	17.92	33.31

See Table 1 for abbreviations.
[a] AMEI levels: 1, 2, and 3.

Table 4
The area of multiple edge influence ($AMEI_i$[a]) to landscape area ratio (ALAR) at three $AMEI_i$ levels with different depth of edge influence (DEI) ranging from 30 to 120 m by main patch types

Main patch types	$ALAR_i$	30 m (%)	60 m (%)	90 m (%)	120 m (%)
RFS	$ALAR_1$	9.49	10.96	9.35	7.50
	$ALAR_2$	1.20	5.24	7.66	8.25
	$ALAR_3$	0.01	0.88	2.90	5.75
MH	$ALAR_1$	9.76	13.42	12.93	11.07
	$ALAR_2$	0.96	4.10	7.23	9.17
	$ALAR_3$	0.01	0.44	1.82	3.96
MHC	$ALAR_1$	12.32	14.05	11.46	8.29
	$ALAR_2$	1.20	5.74	8.86	10.14
	$ALAR_3$	0.01	0.67	2.82	5.69
NFBG	$ALAR_1$	4.12	4.71	3.86	2.99
	$ALAR_2$	0.62	1.95	2.84	2.93
	$ALAR_3$	0.01	0.29	1.24	2.42
JP	$ALAR_1$	1.88	1.24	0.58	0.28
	$ALAR_2$	0.45	1.44	1.41	1.05
	$ALAR_3$	0.01	0.43	1.18	1.84
RP	$ALAR_1$	4.56	5.24	4.15	2.96
	$ALAR_2$	0.72	2.55	3.77	3.90
	$ALAR_3$	0.01	0.38	1.73	3.43

See Table 1 for abbreviations.
[a] AMEI levels: 1, 2, and 3.

Limited studies have included AMEIs in recent ecological research (Malcolm, 1994; Fernandez et al., 2002). Malcolm (1994) and Fernandez et al. (2002) modeled additive multiple edge effects within a region for estimating the total edge effects. However, neither incorporated the theoretical and empirical models into explicitly spatial measures (i.e., as a component of GIS analyses). Mancke and Gavin (2000) developed an edge depth index that incorporated distances to four edges within patches for determining sub-patch level influences to points within a patch. In this study, we looked into the complex boundaries and provided an applicable method to isolate and locate AMEIs with different DEI values for a landscape mosaic. We explicitly located AMEIs and associated quantitative measures reflecting the components of complex patch interactions by patch type, geometry, and landscape patch patterns. Identification of AMEI will enhance our assessment of landscape structure, function, and process. For example, Ries et al. (2004) noted that most studies use the linear distance to

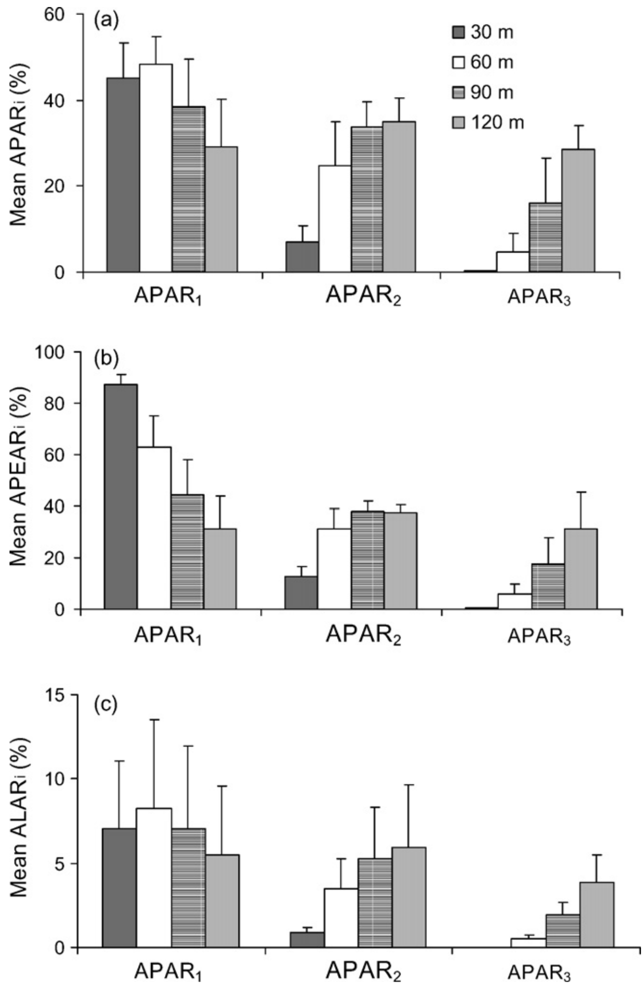

Fig. 4. The mean ratios of: (a) the area of multiple edge influence (AMEI) to the main patch type area (APAR), (b) AMEI to the total main patch edge area (APEAR), and (c) AMEI to the total landscape area (ALAR) at three edge type levels with different depths of edge influence (DEI) ranging from 30 to 120 m at the Chequamegon National Forest (CNF), WI, USA.

the closest edge as the main explanatory variable, and researchers generally avoid placing plots near corners or other converging edge types to limit their potential influence.

In our landscape, the area of multiple edge influence ($AMEI_2$ and $AMEI_3$) ranged from 5% (at 30 m DEI) to 60% (at 120 m DEI; Fig. 3). Most empirical and model researchers missed this additional edge complexity if they only considered a single level of edge structure and treated this structure as $AMEI_1$ in previous empirical and model research (Saunders et al., 1991, 1999; Euskirchen et al., 2001). The patterns of the total AMEI and each component of $AMEI_i$ showed interesting changes as DEI increases. The total AMEI, which is a cumulative effect of all the three components, increased as DEI increased. $AMEI_1$ nonlinearly decreased when DEI increased. $AMEI_2$ increased as DEI increased, and $AMEI_3$ also increased with increasing DEI. These changes hindered three different functional responses of AMEI to the changes of DEI within the given landscape (Fig. 3). Consequently, a positive effect of edges on an ecological process will counteract the effects of increasing area in $AMEI_2$ and $AMEI_3$ at 90 and 120 m DEI. Lastly, changes in $AMEI_2$, different DEI, and patch types may increase if AMEI positively affects DEI at more complex AMEI components.

The amount of $AMEI_1$ varied greatly by patch types and DEI across our landscape (Table 1). The regenerating forests/shrubs $AMEI_1$ had the largest percentage in non-forest bare ground regardless of the DEI. Non-forest bare ground and regenerating forests/shrubs directly resulted from management practices (e.g., clear cutting and prescribed burning). Non-forest bare ground is a short-term patch type lasting 0–5 years, while regenerating forests/shrubs are successional stages between non-forest bare ground and mature patch types, which lasts from 6 to 15 years in our landscape (Zheng et al., 2004). Since 1986, management objectives have shifted the focus to expand and maintain the Pine Barrens through harvesting and prescribed burning. This will increase the adjacency of non-forest bare ground and regenerating forests/shrubs and lead to reciprocated dominance in the $AMEI_1$. Additionally, regenerating forests/shrubs $AMEI_1$ had the second highest percentage in the rest of the patches due to its being a successional stage occurring throughout the landscape. Mixed hardwood/conifer $AMEI_1$ had the greatest influence on mixed hardwood and red pine; red pine had the greatest effect on jack pine, while mixed hardwood had the greatest influence on mixed hardwood/conifer. There are three possibilities contributing to this relationship: first, the spectral signatures of mixed hardwood and mixed hardwood/conifer; mixed hardwood/conifer and red pine are similar, which would reduce the accuracy of image classification; second, management activities have the tendency to harvest hardwoods and leave conifer species within hardwood patches (e.g., white pine was sparsely distributed within hardwood patches across the landscape, which contributed to the distribution of mixed hardwood/conifer adjacent to mixed hardwood); third, mixed hardwood/conifer was a transition between mixed hardwood and jack pine/red pine (Vora, 1993). This phenomenon was probably because of the large proportion of mixed hardwood/conifer $AMEI_1$ in red pine, jack pine and regenerating forests/shrubs. Obviously, the composition of successional chronology of each patch type (i.e., the age structure), similarities (i.e., patch contrast), and harvesting schedule can all contribute to the results of the spatial configurations of a landscape.

We propose AMEI ratios (APAR, APEAR, and ALAR) to better describe multiple edge effects on specific locations at both patch and landscape levels (Fig. 4a–c). These measures are extensions of the edge to patch area ratio concept (Baskent and Jordan, 1995; McGarigal and Cushman, 2002). These ratios treat the whole edge area as a single functional unit; thus, more detailed information within the edge cannot be interpreted. Several factors would affect these measures. First, geometry of the patch: a circular patch shape has a smaller AMEI than an oblong shaped patch. Second, the number of neighboring patches: increasing the number of neighboring patches reduced $AMEI_1$, while increasing $AMEI_2$ and $AMEI_3$. Finally, DEIs: wider DEI will increase $AMEI_2$ and $AMEI_3$. We found that the quantitative measures of AMEIs of the first component were high when DEI was smaller (i.e., <90 m) in our landscape except for jack pine. Generally, the ratios of the first component were higher than those of the second and the third components, while the ratios of the second component were higher than those of the third component, which were due to increasing AMEI complexity and reducing the chances of two patch types that affect the same spatial location. As AMEI reached the most complex component, three or more patch types affected only a few locations. Jack pine had higher ratios at the second component than the first component, probably because jack pine was highly fragmented by insect and disease outbreaks and harvesting practices. Jack pine harvesting increased between 1985 and 2001 due to: (1) stand maturation, (2) non site-specific planting stock, (3) jack pine budworm and gall rust outbreaks (1990–1995), and (4) the expansion of the Pine Barrens, which harvested a large portion of the jack pine stands (Adams et al., 1995; Radeloff et al., 1999, 2000). However, when DEI reached 120 m, the ratios of the second and third components reached the highest for each patch type.

The AMEI calculation methods proposed in this study can also be linked to landscape models to help extrapolate pattern-process relationships related to edge effects. For example, after a simulated harvest using the HARVEST model (Gustafson and Crow, 1996) – a timber harvest allocation simulator – the resultant scenarios could be looked at with the AMEI model to analyze the different levels of AMEIs resulting from the given intensity of the harvests. Another ecological model, FARSITE (Finney, 1998) – a fire spread model – can be improved by adding edges as a unique fuel type to the fuel map (LaCroix et al., in press). Similarly, other models can also be linked with the AMEI delineation method, such as LANDIS (Mladenoff and He, 1999) and NEUTRAL (Gardner and Walters, 2001). Finally, our methods can be used to identify AMEI for other linear landscape structures, such as roads, power line corridors, or stream riparian zones (Watkins et al., 2003; Chen et al., 2006). In conclusion, it is clear that AMEIs, delineated as additional landscape elements, further refine our understanding of edge structure, should increase our ability to study, model and define landscape structure, are associated ecological processes, and help in developing management plans.

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