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Balancing development and forest conservation: the impact of Maryland's Forest Conservation Act on spatial configuration of forest and housing

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We use a unique dataset of land parcels and forest cover, before and after subdivision development, to examine outcomes of Maryland's Forest Conservation Act (FCA). Focusing on the spatial configuration of homes and forests, we compare subdivisions created before and after FCA implementation in 1993. We found minimal impacts of FCA on forest outcomes we considered: houses were as likely to be built in forest before and after FCA, and forest metrics showed increasing fragmentation with development unchanged by FCA regulation. However, the FCA led to a greater proportion of forest located away from houses after development. Other regulatory efforts, particularly zoning and riparian buffer regulations, were consistently related to outcomes we studied. FCA has been successful in preserving forest cover, but a stronger emphasis on connectivity and conservation of large forest patches, particularly for parcels with extensive forest cover, will be helpful in reducing fragmentation and disturbance with development.

Keywords: residential; sprawl; open space; land-use planning

1. Introduction

Across the US, there are widespread concerns about the environmental impacts of residential development, particularly exurban large-lot development, where houses are typically on one acre of land or more (Heimlich and Anderson 2001; Bar-Massada, Radeloff, and Stewart 2014). This type of housing uses individual private septic systems, and thus can extend into rural areas well beyond areas served by sewers, resulting in development that fragments forest and farmland (Brown *et al.* 2005; Gonzalez-Abraham *et al.* 2007; Wilson and Brown 2015; Olofsson *et al.* 2016; Newburn, Lynch, and Wang 2022). Fragmentation, when a large expanse of vegetation is transformed into a number of smaller patches, isolated from each other by development, is widely thought to have a negative effect on ecological processes and biodiversity, both due to the loss of habitat and increase of edge or border between natural vegetation and development (Pfeifer *et al.* 2017). In lower density development, each house serves as an area of disturbance after development is completed, leading to noise and light pollution (Longcore and Rich 2004; Kaushal, Lewis, and

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McCutchan 2006; Holgerson *et al.* 2018), altering potential for carbon storage (Peach *et al.* 2019), and introducing exotic and invasive plant species (Gavier-Pizarro *et al.* 2010; Riitters *et al.* 2018). In exurban areas in different ecosystems, the ecological impacts of houses on wildlife extend up to 180 m (Glennon, Kretser, and Hilty 2015). As development continues, therefore, it may degrade the features, including native vegetation, wildlife populations, and scenic views, that originally attracted residents (Hansen *et al.* 2005; Hostetler and Drake 2009; Milder and Clark 2011; Vaughn *et al.* 2014).

In response to these concerns, jurisdictions use a complex array of land-use regulations and incentives to protect open space and limit the extent and density of housing development (Bengston, Fletcher, and Nelson 2004; Newburn, Lynch, and Wang 2022). Land-use planning may manage development through limitations on infrastructure, for example, creating urban growth boundaries (UGBs) that restrict the expansion of municipal sewer service required for higher density development (Newburn and Berck 2006). Open space, or land that is undeveloped, can be protected through regulations that prohibit disturbance or require mitigation for sensitive ecosystems or areas of native vegetation, such as wetland and riparian buffers. Other regulations focus on the extent and density of housing, most commonly, zoning regulations which dictate land use (e.g. agricultural, residential, commercial use) and determine the density of housing allowed (Bengston, Fletcher, and Nelson 2004; Rudolf, Kienast, and Hersperger 2018).

Over time, as the value of the ecological and social importance of such open space has increased, policy goals have also become more far-reaching. For example, objectives may extend beyond preserving vegetation cover during development to ensuring continued ecological functioning, by maintaining water quality at a landscape scale, minimizing vegetation fragmentation, and maintaining vegetation connectivity within and beyond the subdivision boundary. For example, "conservation development" policies require or incentivize open space protection as part of development, while also clustering housing to reduce fragmentation and the cumulative disturbance created by individual homes (Glennon and Kretser 2013; Glennon, Kretser, and Hilty 2015; Warren *et al.* 2015).

While there is increasing interest in retaining native vegetation and ensuring connectivity along with residential development, the outcomes of such efforts are still poorly understood (Freeman and Bell 2011; Chowdhury and Turner 2019; Gounaridis, Newell, and Goodspeed 2020). Land-use outcomes of regulations are challenging to study, with limited data tracking land-use decisions and vegetation over time (Irwin *et al.* 2019). Even in a single jurisdiction, there are usually multiple policies at work, as well as many different goals, and the interchanges between outcomes and different policies are challenging to tease apart. Thus far, studies of land-use policies typically focus on the amount of open space resulting, with less emphasis on shape, configuration, and function of open space (Wald and Hostetler 2010; Lynch 2021). However, such questions are worth pursuing, given the importance of open space, and because land-use regulations may have unanticipated or unintended effects. For example, efforts to retain open space during development may achieve their goal at the cost of fragmentation (Taylor, Brown, and Larsen 2007) or be diminished if edge effects from housing development extend onto open space (Lenth, Knight, and Gilgert 2006). Similarly, efforts to constrain sprawl though minimum lot size zoning may actually exacerbate sprawl by allowing development only in dispersed patterns on large lots (Robinson, Newell, and Marzluff 2005; McConnell, Walls, and Kopits 2006; Irwin and Bockstael 2007).

Accordingly, our goal in this study is to examine how implementation of a policy requiring forest preservation during subdivision development influenced forest fragmentation within subdivisions and the spatial relationship between houses and forest cover. In the state of Maryland, the Forest Conservation Act (FCA) was implemented in 1993, requiring that all development over 40,000 ft^2 (3,716.1 m^2) map and preserve forest cover, with an emphasis on maintaining connectivity within and beyond development boundaries (among other goals, see more below). Analyses of the FCA have shown it does lead to forest conservation. In Baltimore County, after implementation of the FCA regulation, there was a 21% increase in forest cover within subdivisions relative to the counterfactual without the regulation, with the greatest gains in forest conservation seen in residential subdivisions with low to moderate percentages of existing forest cover prior to development (Newburn and Ferris 2017). However, it is unclear whether or how FCA altered forest fragmentation within subdivision boundaries (decreased, augmented, or had no effect on forest fragmentation). We also examine whether FCA implementation led to any changes in the spatial relationship between houses and forest cover in subdivisions. Although FCA regulations make no explicit provisions for how houses are to be configured in relation to forests, the emphasis on retaining forest cover and maintaining connectivity makes it reasonable to consider how disturbance from development to forest remaining has changed. For example, placing homes in non-forest cover at the time of development would limit forest loss and disturbance with development, while configuring homes such that forest cover remains distant from homes would minimize disturbance after initial development.

Our specific objectives, therefore, were to examine how FCA implementation affected development practice and outcomes in three ways: (1) the likelihood of placing homes in forest at the time of subdivision development; (2) forest cover location in relation to houses, after subdivision development; and (3) changes in forest fragmentation that occurred during subdivision development. Using historic development plat maps with spatially explicit parcel-level tax assessor data, we were able to manually reconstruct parcel subdivision boundaries to examine all residential development activity in rural Baltimore County from 1985 to 2000. Importantly, this includes residential subdivision built before the FCA (1985–1992) and after the FCA was implemented (1993–2000). To characterize forest cover change, we used a longitudinal panel of forest cover data from satellite imagery. Given the complexity of land-use goals and policies, we considered the effects of FCA establishment along with existing land-use regulations, including zoning and requirements for riparian buffer setbacks to protect forests along streams and waterbodies. Our study adds to a limited literature of development and landcover outcomes by empirically assessing the effects of a newly introduced regulation, analyzing forest cover change within multiple subdivisions spanning periods before and after implementation (e.g. Taylor, Brown, and Larsen 2007), and focuses specifically on the spatial configuration of housing and vegetation as outcomes of land-use regulations.

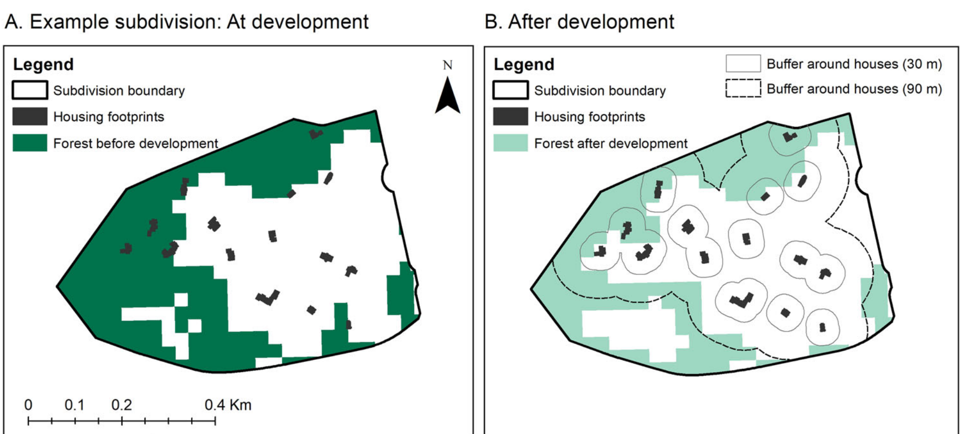
2. Methods

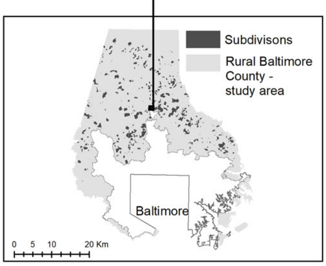
2.1. Study area and land-use policies

Baltimore County extends over 1,575 km^2, surrounding the City of Baltimore and extending north to the state border with Pennsylvania. As with the rest of the Northeast, the area is naturally forested, but forests were extensively harvested and widely converted to agriculture after the arrival of European colonists (Maryland Department of Natural Resources 2020). Much of the forest present today is the result of regrowth and this central region of Maryland today has some of the older forest stands (100 years and older) in the state, with little timber harvesting (Lister and Widmann 2016). Oak forests are the dominant forest group in Baltimore County, as they are throughout the state (Baltimore County 2007) and the broader region (Hanberry and Nowacki 2016).

Baltimore County had a population of over 800,000 in 2010 (the third most populous county in Maryland) (US Census Bureau 2021), with a long history of population growth and land conservation in the post-World War II period (much of the conservation focused on agricultural heritage). In 1967, the county implemented a UGB to limit the municipal sewer service required for higher density suburban development. The majority of housing and population is found within the UGB on municipal sewer service, but the majority of acreage developed and forest loss occurs due to low density exurban development outside the UGB (Baltimore County 2010). The area outside the UGB is two-thirds (1,046 km^2) of the county land area, primarily with low-density exurban development serviced by septic systems (Newburn and Ferris 2016). Our study area was the area outside the UGB (Figure 1). The study area is predominantly forested, with 56.1% and 54.6% forest cover in 1996 and 2004, respectively. Focusing on the area outside the UGB allowed us to concentrate on lower density residential development typical of exurban areas and was more appropriate for the 30 m x 30 m spatial resolution of forest cover data available (see more below).

Zoning regulations in our study area were established in 1976 in three main zoning designations (Newburn and Ferris 2016; Irwin *et al.* 2019). Each zoning designation allows a different maximum density of housing development and a different threshold





Data for Example Subdivision:	Before development	After development
Percent forested	48.4%	35.6%
Housing and forest		
Housing footprints in forest	6/15 (40%) in forest before development	
Percent forest located outside:		
30 m buffer of houses		82.5%
90 m buffer of houses		34.7%
Forest metrics		
Number of patches, NumP	3	3
Mean patch size, MPS (ha)	4.7	3.7
Landscape shape index, LSI	2.5	2.6
Total core area index, TCAI (%)	38.4	24.6
Mean core area, MCA (ha)	1.1	0.6

Figure 1. Housing, forest cover, and forest metrics for an example subdivision (A) before and (B) after housing development.

for forest conservation and afforestation under the FCA (Newburn and Ferris 2017). Agricultural zoning (RC2) has the lowest residential density, with a maximum of one lot per fifty acres, and is intended to preserve agricultural production. Watershed protection zoning (RC4) has a maximum density of one lot per five acres, and is distributed to protect water quality for the three regional reservoirs (Liberty, Loch Raven, and Prettyboy), which supply drinking water to over 1.8 million residents in the Baltimore metropolitan region. Agricultural (RC2) and watershed protection (RC4) zoning areas represent the majority of the study area (Newburn and Ferris 2016). Rural residential zoning (RC5) allows a maximum density of one lot per two acres. These three zoning types remained unchanged during our study period, except that watershed protection (RC4) zoning mandated clustering for residential lots starting in 1993 (Newburn and Ferris 2017).

FCA applies statewide in Maryland, requiring developers to assess, protect, and in some cases, mitigate and augment, forest cover during development (any grading over 40,000 ft^2). As part of the development process, landowners must submit forest stand delineation, mapping existing forest stands, large specimen trees, and sensitive areas. This map is used to identify priority areas for forest protection and restoration. Forest is defined as a biological community dominated by trees and other woody plants covering 10,000 ft^2 (939 m^2), having a minimum density of 100 trees per acre (Galvin, Wilson, and Honeczy 2000). Thus, individual trees for landscaping amenities and street trees are not considered as forest under the FCA requirements. The law states that priority areas include 100-year floodplains, intermittent and perennial streams and their buffers, steep slopes (greater than 25 percent grade), critical habitats for endangered species, non-tidal wetlands, and contiguous forest that connects the largest undeveloped or most vegetated tracts of land within and adjacent to the site (Chesapeake Bay Foundation 2004). Thus, importantly, maintaining forest connectivity within and across subdivision boundaries is explicitly part of the FCA's goals. After priority areas have been identified and mapped, they must be protected under easement.

Under the FCA, there are thresholds for forest conservation that correspond with the land-use zoning for each property. Agricultural (RC2) and watershed protection (RC4) zoning, the majority of land in our study area, have conservation thresholds of 50%. Rural residential (RC5) zoning has a forest conservation threshold of 25%. To avoid replanting requirements, developers must retain at least 20% of the existing forest cover above the conservation threshold, known as the break-even point (Chesapeake Bay Foundation 2004). Forest land cleared below the break-even point but above the conservation threshold must be replanted at one quarter the amount of forest cleared. Forest land cleared below the conservation threshold must be replanted at twice the amount cleared below the conservation threshold (for more information and examples please see Chesapeake Bay Foundation [2004]). Finally, for any subdivisions with less than 20% existing forest cover, developers must plant trees up to 20% (afforestation threshold), even if no trees are cleared during the development process. Prior to the FCA regulations, no conservation or afforestation thresholds existed for the entire region.

Analyses of the FCA have shown it does lead to forest conservation, particularly in parcels with low to moderate forest cover (Newburn and Ferris 2017). However, parcels with the highest levels of forest cover continue to have significant losses, despite the FCA regulations. This is because parcels with the highest level of existing forest cover can clear a substantial amount of forest cover without reaching the break-even point described above that would trigger replanting requirements. Hence, the parcels with the most intact forest cover are those least protected by the FCA regulations.

Riparian buffers are vegetated zones adjacent to streams and wetlands, which play an important role in maintaining water quality, flood control, preventing erosion, and protecting habitat for aquatic and terrestrial species. Baltimore County has riparian buffer setback rules that are adopted at a county level, specifying at least 75 ft buffers (22.9 m), with additional buffer required for wetlands classification, floodplains and surrounding features (slope, potential for erosion) (Baltimore County n.d.). Additionally, the primary residential building must be set back 35 ft (10.7 m) from the buffer edge.

2.2. Data

We used spatially explicit parcel-level tax assessor data from the Maryland Department of Planning. Starting with historic archives of subdivision plat maps, we manually reconstructed each subdivision that occurred between 1985 and 2000. We determined the time of subdivision development based on the year of subdivision approval from the plat map. All parcels in the same subdivision were aggregated to recover the boundaries of the original parent parcel. The residential subdivision history allowed us to group parcels into subdivisions developed prior to FCA establishment from 1985 to 1992 ($n = 240$) and those developed after FCA from 1993 to 2000 ($n = 184$) (see more detail in Newburn and Ferris (2017)). Land cover within subdivisions was classified into forest and non-forest, using 30 m pixel resolution from LANDSAT satellite-based land cover data from the North American Forest Dynamics Project (Goward *et al.* 2012). Forest data were available in 1984, 1986, 1987, 1988, 1990, 1991, 1994, 1996, 1998, 2000, 2002, and 2004. Our study area is the portion of the county outside the UGB for which we have remotely sensed vegetation data (967 km^2).

Following methods from Newburn and Ferris (2017), we calculated the proportion of forest cover before and after subdivision development. The before year is the available satellite image immediately prior to development, and the after year is 1996 and 2004 for all pre- and post-FCA subdivisions, respectively. For example, a subdivision approved in 1988 would use the forest cover from the 1987 image prior to development and the forest cover from the 1996 image to allow several years for the homes to be constructed after subdivision approval. In our sample, four years were the minimum between subdivision approval date and ‘after’ imagery. Parcel-level tax assessor data include the year built for each house in the subdivision and indicates most homes are constructed within four years of subdivision approval. The home construction is the impact on the forest cover, not the subdivision approval (i.e. legal permission to subdivide land and later build homes). For each subdivision, therefore, we had maps of all forest and non-forest cover within subdivision boundaries, before and after subdivision development. We then calculated physical characteristics of subdivisions in GIS, including total parcel acreage, average slope from a digital elevation model (DEM) at 10-meter grid resolution, and proportion of subdivision area within a 100 ft (30.5 m) riparian buffer based on the stream hydrology and 100-year floodplains (see more information in Newburn and Ferris (2017)).

We used building footprint data from Baltimore County (Baltimore County 2018), restricted to solely residential buildings, to determine the location and size of housing footprints in our study subdivisions. Because footprint data are from 2018, and subdivisions were developed from 1985 to 2000, we used historical NAIP aerial imagery (2006 was earliest available) to compare 2018 building footprints to footprints from earlier imagery. We selected 20 subdivisions at random (approximately 5% of our sample) and found that 2018 building footprints were essentially the same as in building footprints in 2006 NAIP, so we concluded it was reasonable to use 2018 footprint data.

2.3. Analyses

Our final dataset, therefore, included 422 subdivisions, before and after FCA establishment. We first conducted descriptive analyses of subdivision size, forest cover, and number of houses, pre- and post-FCA, including t-tests comparing subdivision size and number of houses per subdivision before and after FCA. We then used an observational study design to examine the spatial relationship between buildings and forests in two ways, pre- and post-FCA establishment. We used forest cover data from before development (date selection as described above) to calculate the proportion of a subdivision's buildings placed in forest cover (any building with more than 50% forest cover we deemed placed in forest) (Figure 1). We then calculated the proportion of a subdivision's forest that remained removed from buildings after development, using four different buffers around residential footprints (10, 30, 90, and 180 m), and overlaying the forest cover data from after development (date selection as described above) for all subdivisions that had forest cover present at the time of development and housing footprint data ($n = 404$) (see example subdivision in Figure 1). Past research in exurban areas has found 180 m a reasonable size for disturbance or ecological effect zone (Glennon, Kretser, and Hilty 2015). Given the size and scale of our subdivisions, we also used smaller buffer sizes to more fully examine how forest cover is related to housing placement. We also ran this analysis for a subset of subdivisions, removing those with 100% forest cover (where houses had to be placed in forest cover, $n = 38$), but found results were consistent between the two analyses, so we present findings from the larger dataset of 404 subdivisions.

We then modeled these response measures of the spatial relationship between buildings and forest cover. Our predictor variables included several measures of forest and physical characteristics (proportion of entire subdivision forested before development, area of forest within subdivision before development, and average slope) as well as three variables related to land-use regulations (the proportion of subdivision in the riparian buffer, zoning classification, and if subdivision was developed pre- or post-FCA establishment). Because of changes in watershed protection (RC4) zoning when FCA was enacted we also included an interaction between FCA establishment and zoning. Pearson's correlation analyses confirmed continuous predictor variables were not highly correlated, and multicollinearity was not an issue when we ran linear regressions and evaluated tolerance and variance inflation factors for the continuous variables in the model (Allison 1999). Because both our response variables were proportions (proportion of homes in forest, proportion of forest away from homes with 30 m and 90 m buffers), we used a generalized linear mixed model in PROC GLIMMIX (SAS version 9.3) (SAS Institute Inc 2017). We chose a beta distribution with a logit link function, based on the U-shaped distribution of our response variable. The beta distribution is bounded by zero and one, so we added a small constant to the zero observations and subtracted a small constant from the one observation to keep these observations in the analysis. For categorical variables (zoning, FCA status), we used a Tukey-Kramer adjustment for the least squares means comparisons. In some cases, our model showed that residuals for zoning were visually different (via boxplots) and statistically different (Levene's test). Therefore, we added a separate random intercept for each zoning designation into the model (via group = option in SAS) to correct for heterogeneity of variance). We visually inspected model fits and examined data for larger residuals.

We then calculated landscape fragmentation metrics for forest cover (hereafter, forest cover metrics), for each subdivision, to characterize the spatial distribution of forest cover within subdivisions, before and after development. For these analyses, we excluded subdivisions that had no forest before development, retaining 406 subdivisions. Using forest cover before and after subdivision development, with the dates described above, we calculated a total of five forest cover metrics in Patch Analyst (Rempel 2012), an extension in ArcGIS (see example subdivision in Figure 1). We first used three metrics to characterize the amount and distribution of forest cover: (1) number of forest patches (NumP); (2) mean size of forest patches (MPS); (3) landscape shape index (LSI)–a measure of edge in between forest and non-forest within each subdivision. We then used an additional two metrics to characterize the amount and distribution of 'core forest', that is, the forest away from edges: (4) total core area index (TCAI), the percentage of subdivision that is core area and (5) mean core area (MCA), the average size of core area in forest patches. To determine core areas, we used the default setting in Patch Analyst, which uses 20 m as an edge. We chose these metrics following similar studies that investigated the effects of land-use regulations on subsequent subdivision and forest configuration (Taylor, Brown, and Larsen 2007; Kim and Zhou 2012; Park 2013). Although there are many different landscape metrics that can provide insight into spatial pattern and fragmentation, studies typically focus only on several metrics to avoid duplication (Leitao and Ahern 2002).

We used the long format of data modeling forest cover metrics with a before and after development variable, including subdivision as a random variable, and using the same predictors as above: the proportion of the entire subdivision forested before development, the area of forest within the subdivision before development, average slope, and three variables for land-use regulations—proportion of subdivision in riparian buffer, zoning classification, and if subdivision was developed pre or post FCA establishment. We again included an interaction between FCA establishment and zoning. Using the long format of data allowed us to confirm that metrics reflected changes in forest cover with subdivision establishment (i.e. that our measures of forest fragmentation were changing with subdivision development). Because it was possible that forest shape and configuration would vary with zoning designations and amount of riparian buffer, we also included an interaction between timing of subdivision development (before or after) and zoning designation, as well as timing of subdivision development and riparian buffer. These interactions allowed us to examine how forest metrics changed with development, in relation to the different land-use regulations. Because of the observational nature of the study we used a generalized linear mixed model in PROC GLIMMIX (SAS version 9.3) (SAS Institute Inc. 2017) and eliminated non-significant variables from the model one at a time, re-running models each time a variable was deleted to ensure the other variables remained significant.

For number of forest patches (NumP), model comparisons showed a negative binomial distribution with log link function being the best fit, and for total core area index (TCAI), the normal distribution with identity link function was the best fit, but for all other models (MPS, LSI, MCA), the lognormal distribution with identity link was the best fit. For total core area index (TCAI) alone, we added a separate intercept for each zoning designation into the model (via group = zoning option) to correct for heterogeneity of variance. When analyzing MCA, the interaction between the continuous measure of riparian buffer and timing of subdivision development was examined at the 10th, mean, and 90th percentile of the covariate riparian buffer yielding an unequal slopes model. When appropriate, we reported back-transformed means and standard errors for categorical variables (using ILINK option in SAS for negative binomial distribution and Delta method for lognormal distribution). Given the random subdivision variable in all models, we used the Kenward–Rogers denominator degrees of freedom adjustment method for these analyses. All analyses used an alpha =0.05 as the significance level for the study.

Finally, for all analyses we further conducted a robustness check on our findings, using propensity score matching to consider potential sample selection effects (i.e. if parcels developed had changed in attributes such as forest cover with FCA implementation).

3. Results

In total, we had data on 422 subdivisions containing 3,632 houses, with 1,914 houses placed in forest. We had 240 subdivisions built before FCA regulations, a total size of 44.51 km^2, and 182 subdivisions built after FCA regulations, a total size of 27.12 km^2 (Table 1). Subdivisions developed before and after FCA were similar in size, although those developed before FCA establishment had more houses, on average (a mean of 10.5 vs 6.1), and a lower proportion of area forested (0.55 vs 0.63 m) (Table 1).

3.1. Homes placed in forests

The proportion of houses built in forest cover was significantly related to the proportion of subdivision forested and two land-use regulation variables, zoning and the proportion of the subdivision area in the riparian buffer (Table 2). The area of forest in the subdivision before development, mean slope, FCA establishment, and an

Table 1. Area, forest cover, and houses built for study area and per subdivision, pre- and post-FCA implementation.

Study area	Pre-FCA	Post-FCA
Number of subdivisions	240	182
Total subdivision area (km^2)	44.5	27.1
Number of houses	2,513	1,119
Total forest area:		
Before development (km^2)	27.2	15.0
After development (km^2)	23.3	13.7

	Pre-FCA		Post-FCA		
Per subdivision:	Mean	Standard error	Mean	Standard error	*t*-test
Subdivision area (km^2)	0.19	0.02	0.15	0.02	$t = -1.7$, df = 409.3, p-value = 0.09
Number of houses	10.5	0.85	6.1	0.77	$t = -3.8$, df = 419.2, p-value < 0.001
Proportion forest cover-before develop	0.63	0.02	0.55	0.02	$t = -2.4$, df = 388.4, p-value = 0.02

Table 2. Solution for fixed effects of proportion housing developed in forest (df = 417). For categorical variable (zone), we report back-transformed mean and standard error of the mean.

Variables	Estimate	Standard error	F Value	Pr > F
Prop. forested	7.04	0.27	679.88	<0.0001
Prop. riparian	−2.42	0.45	28.92	<0.0001
Zone-means			4.41	0.01
Agricultural-RC2[A]	0.64	0.04		
Watershed-RC4[B]	0.50	0.03		
Rural residential-RC5[AB]	0.56	0.02		

[AB]Levels with the same letter were not significantly different based on Tukey-Kramer test of LSMeans.

interaction between FCA establishment and zoning did not have a significant effect on the proportion of houses built in forest cover and was excluded from the final model. We inspected residuals and found that the model fit was adequate, with some larger residuals for subdivisions that had few houses and thus tended to have more extreme values for the proportion of homes placed in forest as a result.

Estimates of fixed effects in the final model revealed the proportion of subdivision forested had a strong positive relationship to our response variable; not surprisingly more houses were placed in forest in subdivisions that had a greater proportion of forest cover before development (Table 2). Houses were significantly less likely to be placed in forest with a higher proportion of subdivision protected as a riparian buffer. A Tukey-Kramer test comparison between zoning designations showed that houses were less likely to be placed in forest in the watershed protection (RC4) zoning than in the agricultural protection (RC2) zone. Rural residential (RC5) zones were not statistically different from the other two zoning designations (Table 2).

3.2. Forest cover location in relation to houses

We examined four different buffer distances to determine how to best measure the extent of forest cover in relation to houses after subdivision development. Nearly all of the subdivisions' forest cover was outside the 10 m buffer around homes or within 180 m buffers (Figure 2). Therefore, we focused on 30 m and 90 m buffers for modeling. With a 30 m buffer, on average, 73.8% of subdivisions' forest remained away from houses (std. error = 1.07), while with a 90 m buffer, on average 35.4% of subdivisions' forest remained away from houses (std. error = 1.49).

For both 30 m and 90 m buffers, final models included the proportion of subdivision forested before development, the area of forest before development, and all three land-use regulation variables (riparian zone, zoning designation, and FCA establishment), with slope retained for the 30 m buffer model only (Table 3). For both final models we inspected residuals and found that the fit was adequate, with some larger residuals for the 30 m buffer model, in subdivisions that had the smallest values for the proportion of riparian buffer and area forest cover.

For both buffer distances, the proportion of forest located away from homes was positively related to the area forested before development, but negatively related to the proportion of subdivision covered with forest before development (i.e. as the proportion of the subdivision forested increased, less forest remained away from houses) (Table 3). Slope was retained only in the 30 m buffer model, and positively related to the proportion

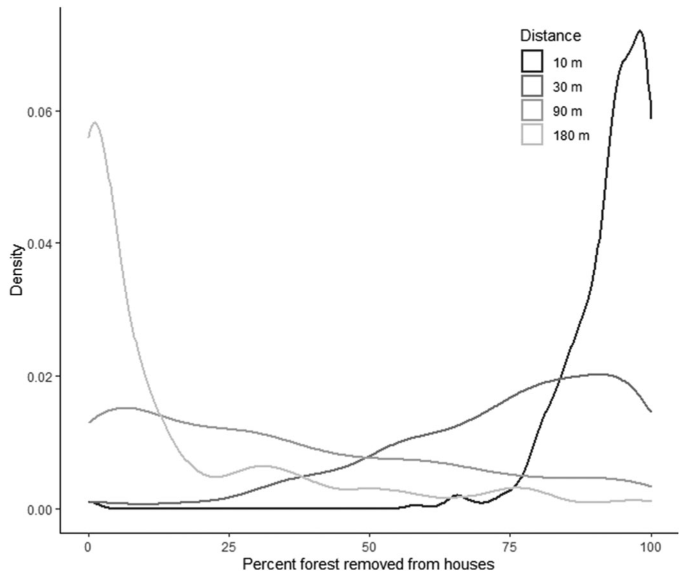


Figure 2. Density plot for subdivisions' proportion of forest located away from houses by different buffer sizes (10, 30, 90, and 180 m).

of forest removed from houses. All three land-use regulation variables, FCA establishment, riparian buffers, and zoning were retained in some of the final models. Subdivisions developed post-FCA establishment had a higher proportion of forest located away from homes in comparison to subdivisions developed pre-FCA, for both 30 m and 90 m buffers (Table 3).

The proportion of subdivision protected in the riparian buffer was also positively related to the proportion of forested located away from homes after development, for both buffers (Table 3).

The effect of zoning differed for the two buffer distance models. For both the 30 m and 90 m buffer, the Tukey–Kramer test comparison revealed the proportion of forest removed from houses was lowest for rural residential (RC5) zoning (Table 3). For 30 m buffers, the proportion of forest away from homes was highest for watershed protection zoning (RC4) and intermediate for agricultural (RC2) zoning (the two were statistically significantly different) (Table 3). For the 90 m buffers agricultural (RC2) and watershed protection (RC4) zoning had more forest remaining away from houses than rural residential, but agriculture (RC2) and watershed protection (RC4) were not statistically significantly different from each other (Table 3). Interaction between zoning and FCA establishment was not significant or included in either model.

3.3. Forest cover metrics and subdivision development

For all forest cover metrics, the before and after development variable was included in the final model, demonstrating that these metrics did change with subdivision development. After subdivisions were developed, the number of patches (NumP) increased, as did LSI, or shape complexity of forest patches (Table 4). Mean patch size (MPS) decreased after subdivision development, as did both measures of core forest, percent

Table 3. Solution for fixed effects of proportion of forest distant from homes 30 m and 90 m buffers ($n = 402$). For categorical variables (zone, FCA) we report back-transformed mean and standard error of the mean.

	30 m					90 m				
Variables	Estimate	Standard error	Den DF	F value	Pr > F	Estimate	Standard error	Den DF	F value	Pr > F
Prop. forested before	0.81	0.15	322.50	45.53	<.0001	−0.68	0.18	68.50	48.49	<.0001
Area forested before	−1.22	0.18	235.70	7.97	0.005	−1.62	0.23	73.51	24.81	<.0001
Prop. riparian	1.01	0.36	275.10	28.03	<.0001	2.36	0.47	74.59	26.40	<.0001
Slope	1.95	0.37	274.80	4.77	0.03	2.60	0.51			
Zone-means			240.00	41.37	<.0001			63.21	23.63	<.0001
Agriculture-RC2	0.78^{B}	0.02				0.43^{A}	0.03			
Watershed-RC4	0.84^{A}	0.01				0.42^{A}	0.03			
Rural residential-RC5	0.67^{C}	0.02				0.23^{B}	0.02			
FCA-means			294.5	5.49	0.02			71.82	12.48	0.0007
Pre	0.75^{b}	0.01				0.30^{ab}	0.02			
Post	$0.79^{\underline{a}}$	0.01				0.40^{ba}	0.02			

^{ABC}Levels with the same letter were not significantly different based on Tukey–Kramer test of LS-means.
^{ab}Levels with the same letter were not significantly different based on Tukey–Kramer test of LS-means.

Table 4. Summary statistics for forest cover metrics, before and after subdivision development ($n = 406$).

	Number of Patches (NumP)		Mean Patch Size (MPS) (ha)		Landscape Shape Index (LSI)		Total Core Area Index (TCAI) %		Mean Core Area (MCA) (ha)	
	Before	After	Before	After	Before	After	Before	After	Before	After
Mean	2.3	2.6	6.4	4.7	2.1	2.2	35.9	32.1	3.6	2.6
Std. error	0.11	0.13	0.50	0.33	0.03	0.03	1.19	1.13	0.32	0.22
Min	1	1	0.08	0.08	1.05	1.05	0	0	0	0
Max	23	24	99.9	56.4	5.4	5.2	84.3	83.6	53.6	39.7

of subdivision in core area (TCAI) and average size of core forest in patches (MCA) (Table 4). For all models we inspected residuals and found that the model fit was adequate, with some larger residuals for subdivisions with larger subdivision area or greater proportion of forest cover prior to development (for TCAI and LSI).

Among all forest cover metrics we considered, the area of subdivision forested and proportion of subdivision forested were retained in all final models (Table 5). However, among land-use regulation variables, FCA establishment was not retained in any final models, while proportion riparian buffer and zoning were typically in each final model (i.e. all metrics except NumP had either or both of these in the final model. Below, we present results from each forest metric in turn.

The number of forested patches in a subdivision (NumP) was positively related to the area forested before development, but negatively related to the proportion of subdivision forested (i.e. as a greater proportion of a subdivision was forested, forest was found in fewer patches) (Table 5). No land-use regulation variables were retained for this variable

Mean patch size was positively related to both area forested before development and proportion of subdivision forested. Two land-use policies, riparian buffer and zoning, were significantly related to MPS. Forest patch size was positively associated with the proportion of subdivision protected as riparian buffer. Subdivisions zoned for watershed protection (RC4) also had larger MPS. There were no significant interactions between these land-use policies and the time of development, indicating that this metric was consistent across zoning designations and the proportion of subdivisions in the riparian buffer, before and after development.

The complexity, or shape, of forest patches, as measured by LSI, was positively related to area forested before development, but negatively related to proportion of subdivision forested before development (i.e. as a greater proportion of a subdivision was forested, forest patches were more compact in shape). Zoning was the only land-use regulation significantly related to LSI. Post-hoc tests showed that watershed protection (RC4) had more complex forest shapes than agricultural protection (RC2), while rural residential (RC5) zoning was not statistically different from either designation (Table 5). However, zoning designations did not alter how LSI changed with development (i.e. no statistically significant interaction between zoning and timing of development).

Both measures of forest core, total core area index (TCAI) and mean core area (MCA), were significantly and positively related to the area and proportion of forest

Table 5. Solution for fixed effects of forest fragmentation measures ($n = 406$). All models with lognormal distribution and identity link, unless noted. For categorical variables (zone, FCA) we report back-transformed mean and standard error of the mean, as needed.

	NumP$				Landscape Shape Index (LSI)				Mean Patch Size (MPS) (ha)			
Effect	Estimate	Std. error	F value	Pr > F	Estimate	Std. error	F value	Pr > F	Estimate	Std. error	F value	Pr > F
Prop. forested before	−1.42	0.11	168.52	<.0001	−0.31	0.04	73.61	<.0001	2.35	0.12	370.61	<.0001
Area forested before	2.19	0.19	130.09	<.0001	1.19	0.08	235.35	<.0001	4.44	0.26	291.06	<.0001
Prop. riparian									1.43	0.28	26.25	<.0001
Subdivision devel.			8.84	0.003			22.87	<.0001			77.80	<.0001
After	2.25^{A}	0.09			2.09^{A}	0.02			2.17^{B}	0.08		
Before	1.97^{B}	0.08			2.03^{B}	0.02			2.72^{A}	0.10		
Zone							4.34	0.014			5.69	0.004
Agriculture-RC2					1.97^{b}	0.03			2.21^{b}	0.13		
Watershed-RC4					2.13^{a}	0.05			2.93^{a}	0.21		
Rural residential-RC5					2.07^{ab}	0.04			2.21^{b}	0.12		

	Total Core Area Index (TCAI)#&				Mean Core Area (MCA) (ha)			
Effect	Estimate	Std. error	F value	Pr > F	Estimate	Std. error	F value	Pr > F
Prop. forested before	37.29	2.27	269.57	<.0001	4.17	0.36	129.17	<.0001
Area forested before	71.80	4.82	221.87	<.0001	7.48	0.73	105.59	<.0001
Prop. riparian	29.73	5.13	33.61	<.0001	3.44	0.82	23.69	<.0001
Slope					0.07	0.03	5.87	0.016
Subdivision devel.			96.60	<.0001			31.65	<.0001
After	32.3^{B}	0.67			0.37^{B}	0.04		
Before	36.0^{A}	0.67			0.53^{A}	0.05		
Zone*FCA			3.14	0.025				
Zone*Subdivision devel.			5.77	0.003			2.64	0.034
Riparian*Subdivsion devel.							4.8	0.029

[AB]Levels with the same letter were not significantly different based on Tukey-Kramer test of LS-means.
[ab] Levels with the same letter were not significantly different based on Tukey-Kramer test of LS-means.
[$]Negative binomial distribution and log link.
[#]Normal distribution and identity link.
[&]group = zone as random intercept.

before development as well as the proportion of the subdivision in the riparian buffer, but other variables retained varied. For TCAI, zoning was retained in the final model, as well as two interactions with zoning (with timing of subdivision development and with FCA establishment). However, Tukey's post-hoc comparisons revealed that TCAI did not differ significantly among zoning types before development, that for each zone, the decline in TCAI was significant. Similarly, the developments created pre-FCA establishment did not show any statistically significant differences in TCAI measures among zoning types, nor did those developed post-FCA.

For the other measure of forest core, MCA, this was the only forest metric to include slope in the final model, with larger values of MCA with greater slopes. Our final model included two interaction terms with timing of subdivision development, zoning and proportion of riparian buffer. Tukey's post-hoc tests revealed that MCA did not differ significantly among zones before development, and that MCA declined significantly after subdivisions were developed in the agricultural (RC2) and rural residential (RC5) zoning only (for watershed protection (RC4) zoning, MCA was not significantly different before and after development). For the interaction between the continuous measure of riparian buffer and timing of subdivision development MCA was consistently statistically lower after subdivision development than before.

Accordingly, although proportions of riparian buffer and zoning designations were retained in several final models, closer analysis of the interactions revealed limited ways that outcomes of development were changing with land-use regulations. Only for MCA did we see a change in how land in different zoning designations fared with development, where watershed protection (RC4) zone subdivisions retained more forest fore area, as measured by MCA, with development.

3.4. Propensity score matching analysis on FCA effects

One potential concern worth considering is the causal identification for the FCA regulation on different outcome variables. The proportion of forest cover before development was consistently important in our models, but developers in the post-FCA period may be deliberately selecting parcels for residential subdivisions with different initial forest cover, leading to a potential sample selection issue. If this is the case, then controlling for the proportion of area forested before subdivision in the results for all regression analysis described above may mask the effect of the FCA. We first performed a t-test for the proportion of forest cover before development, in pre- and post-FCA subdivisions, which was statistically significant (Table 1).

Accordingly, we used propensity score matching (PSM) as a robustness test to examine the causal identification for the effect of the FCA regulation on each of the eight outcome variables described above. The first stage of the PSM analysis used a logit regression model where the post-FCA subdivisions are the treatment group and pre-FCA subdivisions were the control group. The covariates in the logit regression model included the initial percent forest cover, subdivision area, forest area-before, slope, and proportion riparian. The PSM analysis used kernel matching, and all covariates for post-matched controls were balanced. We then used PSM to estimate the average treatment effect on the treated (ATT) for each of the eight dependent variables (Table S1, Supplementary material). Note that the ATT is statistically significant when the 95% confidence intervals do not contain zero.

Overall, the PSM results are largely consistent with those outcomes described above (see Tables 2, 3, and 5), except for one of the eight outcome variables on the forest remaining away from houses (30 m buffer) (Table S1, Supplementary material). In Table 3, the FCA regulation does have a significant effect on forest remaining away from houses for both the 90-meter and 30-meter buffer, described in Section 3.2. The PSM results (Table S1, Supplementary material) show that the FCA does have an ATT that is statistically significant for the 90-meter buffer; meanwhile the ATT for the 30-meter buffer is not statistically significant at the 95% confidence level, since the interval does overlap with zero (-0.083, 0.0003), although it would be significant at the 90% confidence level. All other outcomes are not statistically significant in Tables 2 and 5 and corresponding results from PSM analyses (Table S1, Supplementary material). For instance, the ‘houses in forest cover’ variable is not statistically significant in the PSM table (Table S1, Supplementary material), which is consistent with the result in Table 2 described in Section 3.1. All five of the landscape metrics (NumP, MPS, LSI, TCAI, and MCA) are not statistically significant in the PSM table (Table S1, Supplementary material), which is consistent with the results in Table 5, described above in Section 3.3.

4. Discussion

The amount of land now found in low-density exurban development, and the apparent value that millions of Americans place on living in these settings, demonstrate both the challenge and importance of conserving ecological functioning in residential settings (Radeloff *et al.* 2018; Gounaridis, Newell, and Goodspeed 2020). Even when development is dense, retaining forests and open space within residential landscapes can provide important contributions to ecosystem services and connectivity (Ossola *et al.* 2019). Efforts such as the FCA seek to balance forest conservation and development. However, despite the FCA’s success in conserving significant amounts of forest cover during subdivision development (Newburn and Ferris 2017), we found limited effects of FCA regulation on forest configuration, including forest metrics and the spatial relationship between houses and forests.

FCA establishment was significantly related to only one of the outcomes we studied, the proportion of forest cover that remained distant from houses (i.e. further from the ecological effect zone of houses), and after controlling for sample selection issues, remained only when using a buffer size of 90 m (findings with a 30 m buffer were no longer significant once we controlled for the smaller proportion of forest cover before development). Although post-FCA subdivisions had fewer homes, the likelihood of homes being placed in forests did not change with FCA establishment—on average, 50% or more houses per subdivision were placed in forest cover throughout the study period. More information on disturbance and effects on forests and natural resources at the different buffers we studied will be helpful in determining how this change contributes to maintaining ecological processes. In exurban areas, ecological effect zones of homes on wildlife have persisted out to 180 m or more (Glennon and Kretser 2013; Glennon, Kretser, and Hilty 2015; Warren *et al.* 2015), but at the scale of the subdivisions in our study, nearly all forest was within 180 m of houses.

Overall forest fragmentation that occurred with development did not change with FCA implementation; a result that remained consistent when controlling for sample size selection with PSM. The interpretation of these metrics is complex, as there is no one index or measurement that indicates 'less' or 'more' connectivity or fragmentation. However, with the number of forest patches, mean patch size, the edge or complexity of forest shapes, and measures of forest core area all unaffected by FCA implementation, we think it is reasonable to conclude that FCA had no obvious effect on forest fragmentation within subdivisions. Given that maintaining forest connectivity and larger areas of forest within subdivision borders is an explicit goal of the FCA we were surprised to find that our analyses of forest cover metrics showed no effect of the FCA regulations.

However, the design of the FCA regulations means that subdivisions with the highest levels of forest cover before development can remove a substantial amount of forest cover without reaching the break-even point triggering forest planting requirements (Newburn and Ferris 2017), which might be part of why forest metrics did not change with FCA regulations. We do note that FCA regulations did achieve these forest cover conservation goals without *augmenting* fragmentation. In contrast, Taylor, Brown, and Larsen (2007) used similar resolution land cover data and study design and found that an open space conservation policy in Michigan resulted in more open space preserved within subdivisions, but at the cost of increasing open space fragmentation (more patches and more edge between open space and residential areas). Lynch (2021) suggests that language about connectivity in land-use regulations and plans may connote an assumption that preserving open space and green space will eventually yield connectivity benefits, as a critical mass of desired open space is retained. If so, however, the proportion of forest cover preserved may need to be larger, or requirements about connectivity more explicit, to yield the desired outcomes within subdivisions in our study area. Recently there has been increased interest from conservation organizations in revising FCA regulations, which are now almost 30 years old, in order to support statewide goals for no net loss in forests (Prost 2017; Shaver 2021). Such efforts could also further consider connectivity within, and beyond subdivisions.

Further analyses of FCA planning documents and outcomes could also shed more light on how the spatial configuration of forested areas is changing with subdivision development. Given that the FCA emphasis on connectivity is mentioned along with a number of other priorities for conservation (e.g. steep slopes, wetlands, endangered species), studies could further assess the forest stand delineation and site development plan documentation to better understand how and where forests are being prioritized for conservation. For example, we only considered slope at the level of the subdivision, not within subdivisions, or the slope of forest remaining. Such forest stand delineation and site development plan documents are required by the FCA (Galvin, Wilson, and Honeczy 2000), but have only recently been available digitally. In addition to finer grained information on forest conservation within subdivisions, future studies could also consider connectivity with forested areas beyond subdivision boundaries, as the discussion of connectivity in the FCA also mentions forested areas outside the subdivision. Creating open space connections between different subdivisions is more complex because it requires linking across both space and time—with developments created at different times, by different developers, and potentially under different regulations (Lynch 2021). Such an undertaking, including assessing how such forest cover outside subdivision boundaries might also change over time, was beyond the scope of this study. Finally, our study focused on housing development as a locus for disturbance, but subdivision development and residential use result in many different types of ecological disturbance. For example, some of the forest removed during this process was to construct roads, which alter biotic and abiotic processes, both within and beyond subdivision boundaries (Coffin 2007).

In contrast to FCA, we did find that riparian buffer regulations in Baltimore County were positively influencing many of the forest outcomes we considered. When the subdivision had a higher proportion of area in the riparian buffer, there were fewer homes placed in forest, more forest remained away from houses, and forest remained in larger mean patches, with more forest core. Our findings confirm other studies of riparian buffers in Baltimore County, which have found them effective in reducing the overall likelihood of development and in augmenting the amount of forest preserved during development (Newburn and Ferris 2017; Spurlock 2019).

Finally, Baltimore County also has a long history of using zoning to manage housing growth, particularly in agricultural (RC2) and watershed protection (RC4) zoning (Newburn and Ferris 2016). Among zoning designations, we found watershed protection (RC4) zoning was most strongly associated with forest conservation outcomes: these subdivisions had fewer homes placed in forests and more forest remaining away from homes, and retained similar sizes of forest core with development. Given the aims of this zoning designation, created to protect metropolitan Baltimore's public water supply by limiting the impact of development on three critical reservoir watersheds, these are positive findings. Distinctions between the other zoning types were less clear – for example, subdivisions in rural residential (RC5) zoning had more forest in proximity to houses after development while those in agricultural (RC2) zoning had more houses placed in forest.

4.1. Limitations and additional considerations for landscape-level outcomes

Studying forest cover with subdivision development, before and after regulations are implemented, is a difficult undertaking and there were some limitations with our study. We did not have equivalent data from a 'control' location which was not affected by FCA implementation. However, following previous robustness checks (including varying the time period studied) (Newburn and Ferris 2017) we feel confident that comparing subdivisions before and after FCA establishment is appropriate. To investigate forest cover change over the interval of our study we had to rely on 30 m × 30 m land cover pixels, which is of moderate resolution. Although this resolution has been successfully used to track changes in forest cover over time, and we were able to discern the effects of subdivision development and differences between zoning designations, assessments of connectivity and forest shape will likely differ when assessed with higher resolution forest cover (Wickham and Riitters 2019). Such higher resolution (e.g. 1 m pixel) data is increasingly used to examine forest presence and quality, even in areas with dense development (e.g. Gounaridis, Newell, and Goodspeed 2020).

Extending beyond forest cover to a deeper understanding of forest ecological function would also be helpful, at subdivision- and landscape-levels. We focused only on subdivision development as a time when forests are altered, but did not further examine how disturbance continued over time, around homes and roads (Theobald 2013; Habrich, Lawrence, and Fraser 2021; Glennon and Kretser 2021). In addition to more data about the effects of housing disturbance at smaller distances to forest (e.g. 90 m vs 180 m), additional study could provide more insight into the merits of different spatial configurations of forests, and resultant contributions to other goals such as wildlife habitat or water quality (Brown and Quinn 2018; Wrenn, Klaiber, and Newburn 2019; Gounaridis, Newell, and Goodspeed 2020; Rieb and Bennett 2020). While we focused on traditional metrics of forest fragmentation, we acknowledge that smaller patches of forest also have value (e.g. small forest patches still provide connectivity across landscapes, sources for recolonization, and habitat for edge species) (Kim 2019). Identifying how people benefit directly and indirectly from ecological connectivity can also further support such efforts to sustain and enhance connectivity (Butler *et al.* 2022).

Ultimately, forest management and land-use regulations in Maryland, and throughout the United States remain complex. For example, we were able to consider some different aspects of land-use regulation—zoning, riparian buffers, and FCA—but a deeper understanding of how development design plays out over time in response to these requirements and affects ecological processes would further enhance our understanding of the value and impact of these efforts, alone and in combination. Continuing such research and integrating findings with practitioners and community stakeholders will remain a critical, but challenging, part of improving residential landscape design (Butler *et al.* 2022). However, given the long-term implications of development design on ecological function, it is worthy of sustained investment from the planning and research communities.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Supplemental data

Supplemental data for this article can be accessed here.

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