CONTRIBUTED PAPER





Modeling alternative future scenarios for direct application in land use and conservation planning

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Abstract

Land use is one of the largest threats to biodiversity, ecosystem function, and ecosystem services. These losses can be mitigated through strategic land use planning efforts that balance the social, economic, and environmental needs of society and the ecosystems that support it. A crucial component in the development of strategic plans is a concrete understanding of land use change and the impacts and influence of it on the landscape. Land change models are one method for quantifying the effect of these relationships and projecting the resulting changes on landscapes of the future. However, in order for the resulting model products to be useful to planners, policy makers, and conservationists, they must be focused on addressing questions of relevance to the community they intend to serve. Scenario planning offers a framework for integrating community-developed visions of the future with land change models in order to increase relevancy and uptake of products. We developed a land change model for five future scenarios of land use change in northwestern Virginia, integrating regional stakeholder knowledge throughout the process. Across scenarios, we found consistent increases in development across our study area, but the form and configuration of land use types varied sub-regionally. This manuscript describes not only our results, but the process of integrating stakeholder input throughout. We describe our model outputs in the context of usefulness for planners, policy makers, and conservation decision makers, often through the lens of the importance of geographic scale. This work serves as an additional example of land use modeling across scenarios. We conclude with guidance for scientists interested in integrating similar approaches in their work.

KEYWORDS

actionable science, co-production of knowledge, land use modeling, scenario planning

INTRODUCTION 1

Land use change, such as urbanization, agriculture, and deforestation represents one of the largest contributions

to global environmental change (Riitters et al., 2012; Song et al., 2018; Venter et al., 2016). As the human population continues to grow, rates of resource demand and land use will increase, further degrading ecosystem

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function and the provision of services essential to human survival (Stenseke, 2016; Venter et al., 2016). Realizing a sustainable future requires strategic land use planning efforts that evaluate and balance the resource needs of both humans and ecosystems (Convention on Biological Diversity Secretariat, 2010; Dang & Kawasaki, 2016; IPBES, 2019; Margules & Pressey, 2000). Continually improving satellite data and modeling approaches have enabled the conservation science community to quantify land use change at both small and large geographic scales and develop models that investigate the relationships land use change has with human society and ecological health (Turner et al., 2020). However, in order for this knowledge to effectively influence land use planning and policy, it must be both informative and relevant to the communities it is intended to serve. Unfortunately, often potentially useful information lacks this relevance due to limited stakeholder involvement throughout the process (Zscheischler, 2021). The result is a continuation of ad hoc or reactive planning that furthers the degradation of natural resources.

Broadly, land use change is driven by geography, the economy, the environment, and local community values. The type, amount, and configuration of resulting land use across a landscape impacts the daily lives of human society by establishing where people live, work, and travel. In addition, land use configuration influences the capacity for ecosystems to supply services that are essential to human well-being (Blumstein & Thompson, 2015; Lamy et al., 2016). Recognizing the influence that land use exerts on the environment and human well-being, governments and other decision-making bodies adopt land use plans that consider community needs and also help to mitigate adverse impacts of improper land use (Nolon, 2005). As such the conservation community has for many years proposed that impacts of development on biodiversity and ecosystem function could be reduced by including components of ecosystem function or biodiversity as community needs to be planned for; increasingly through the framework of ecosystem services (Ronchi, 2021). The spatial configuration of land use across a landscape is one metric that may be used to quantify the potential impact of land use on biodiversity, ecosystem function, and ecosystem services (Haddad et al., 2015; Lamy et al., 2016; McGarigal et al., 2018).

Modern GIS and the increased availability of spatial data provide conservation scientists an opportunity to objectively examine the influences and potential outcomes of land use planning on biodiversity, ecosystem function, and ecosystem services across the landscape, aiding in the development of strategic plans. By comparing differences in the location, amount, and configurations of Land Use/Land Cover classes (LULCs) in satellite-derived

landscapes representing differing years, we can quantify land use change. Land Change Models (LCMs) relate land use change with spatially explicit biotic and abiotic environmental data, as well as geographically defined socioeconomic data to explore their relationships (Dang & Kawasaki, 2016). LCMs can therefore provide an understanding of how the physical shape of a landscape, its environment, and socio-economic features of human society (e.g., population density, demography, and wealth) influence the amount and configuration of land use change on a landscape. Further, when combined with an understanding of how land use patterns affect natural resources and ecosystem function, LCMs can be used to quantify impacts, now and in the future (Krause et al., 2019; Stürck et al., 2015; Zscheischler, 2021). Therefore, LCMs have the potential to be highly informative to planners and policy makers in planning for a sustainable future that balances human needs with ecosystem health.

The design of LCM's can vary strongly though, so in order for them to bridge the science-policy divide and successfully advance a region's strategic plans, conservation scientists must parameterize LCMs in such a way that they specifically relate to the needs of communities and their decision makers and incorporate data that relate to the impacts of interest. For conservation decision makers, these impacts may include impacts to water quality, habitat connectivity, or the spread of invasive species to name a few examples. The process of building useful LCM's must be transdisciplinary and collaborative and their products and tools must be co-produced and accessible. (Cash et al., 2002; Castella et al., 2014; Cook et al., 2013; Mayer et al., 2016; White et al., 2015). Moreover, the geographic range and spatial resolution should be appropriate for the jurisdictional boundaries of land use planning decisions (Kettenring & Adams, 2011; Opdam et al., 2013). Unfortunately, often the process of model development, and land change science itself, lacks the full suite of these characteristics, particularly those related to community involvement (Zscheischler, 2021). However, when scientists consider community interests at the onset and throughout the scientific process, evidence shows the likelihood of uptake in planning and policy improves (Bednarek et al., 2018; Mayer et al., 2016).

Scenario planning offers a constructive framework for incorporating diverse community viewpoints into the development of informational products designed for strategic planning. Also referred to as alternative futures planning, scenario planning is an ideal approach when dealing with decisions whose outcomes are both highly uncertain and impactful, such as those in the environmental planning field (Hulse et al., 2004; Kass et al., 2011; Peterson et al., 2003; Rowland et al., 2014). Scenario planning involves the creation of alternate futures based on current data and guided by the knowledge and vision of the community. This improves project credibility and increases the relevance and saliency of the resulting information to the end user (Oteros-Rozas et al., 2015). Scenario planning also forms a key component of frameworks for integrating land use science in plan development, like the growing field of Geodesign (Debnath Petitt & Leao 2022; Gu et al., 2018; Shearer, 2022). LCMs can model scenarios by altering trend parameters to simulate each scenario future. For example, a scenario with higher rates of population growth can be represented in an LCM by increasing the area or density of development. In this way, the use of future scenarios in land use planning helps conservation practitioners and planners alike understand the pathways from stakeholder interests to land use decisions to landscape outcomes. These pathways can be developed into actionable plans whereby key decision makers can be identified along with potential timelines and avenues for policy influence. Once these hypothetical links are made, it is far easier to develop a plan for how to achieve desired outcomes for the future and who to involve in the process.

This paper outlines the development and results of a dynamic, spatially explicit land use model, which incorporates social and environmental knowledge from scientific experts and regional stakeholders. We used this model to project potential land use change across five stakeholderdeveloped land use change scenarios at a 50-year timeframe. Our aim was to understand the consequence of divergent planning strategies and population growth in order to inform strategic, conservation-oriented planning and policy making. To best provide for the breadth of planners and practitioners involved in this aim, our analysis allowed for local policies to influence the impact of largescale drivers of change on resulting land use at a scale relevant to decision makers. The initial motivation for this study stemmed from regional conservation organizations interested in understanding and communicating the benefits of strategic land use planning to preserve biodiversity, ecosystem function, and ecosystem services.

2 **METHODS**

2.1 Study area

Our study area is a 15-county, 17,899 km² area of northwestern Virginia immediately surrounding the Shenandoah National Park (SNP) in the Blue Ridge mountains (Figure 1). The study area includes the northern portions of the Ridge and Valley, Blue Ridge, and Northern Piedmont ecoregions. The watershed of the Shenandoah

River occupies the largest portion of the study area followed by the Rappahannock, James, and York Rivers, all of which drain into the Chesapeake Bay. The area's 2011 population was more than 1 million people (American Community Survey Office, 2012) with large population centers represented by five independent cities located along major thoroughfares, such as Interstate 81 in the Shenandoah Valley. Additionally, populations in the northeastern portion of the study area are growing rapidly due to its proximity to the Washington DC/Baltimore metropolitan areas, a trend that is expected to continue (Weldon Cooper Center for Public Service Demographics Research Group, 2017). More than half of the study area is forest, with contiguous forest occurring mostly at higher elevations, within U.S. Forest Service and the National Park Service land. Most of the remaining study area is privately owned, consisting of a mosaic of smaller forest patches, cropland, grasses, and development. This is typical of land protection patterns in the eastern U.S. where the majority of land is privately owned and under minimal regulatory protection increasing concerns about habitat fragmentation and placing a premium on land use planning for landscape structure (Jenkins et al., 2015; Lacher, Akre, McShea, & Fergus, 2019a). Forests in this region are almost all secondary growth and primarily deciduous with significant oak and hickory stands along with pines, tulip poplars, and core hardwoods (Young et al., 2009). These forested areas provide habitat for iconic species like black bears and bobcats as well as threatened and endangered species like the wood turtle (Willey et al., 2022) and the endemic Shenandoah salamander (Carpenter et al., 2001). Grasses in the region vary between native meadows, agricultural pasture and havfields, and even large residential lawns. Depending on how the fields are managed, however, even working lands can be important habitat for numerous species, particularly birds (Johnson et al., 2019).

2.2 Stakeholder engagement

We used scenario planning as a framework (e.g., Oteros-Rozas et al., 2015; Peterson et al., 2003; Rowland et al., 2014) for co-producing a land change model with a diverse, interdisciplinary group of stakeholders for landscapes in northwestern Virginia. We identified stakeholders initially with guidance from our "core advisory group," a small group of highly motivated individuals with extensive experience and knowledge in planning and conservation in the study area. This "core advisory group" provided guidance throughout the process and remain instrumental in networking, relationship building, and messaging. We were then able to identify additional



FIGURE 1 Location of study area in northwestern Virginia displaying reclassified National Land Cover Database land use/land cover classes in 2011, the study area counties, the eight analysis sub-regions, and the 25 km buffer

stakeholders by way of our growing network through either recommendations or advocacy of our project. We engaged stakeholders through one-on-one communication, interviews, and, in particular, structured workshops detailed below. Participating stakeholders self-declared their expertise to be in topics including agriculture, natural resource use, land use planning/policy, economic development, and conservation management among others. Participants represented positions in county, state, and federal governments as well as local and regional nongovernmental organizations. Throughout our engagement, these stakeholders contributed knowledge on current policies, political views, regional values, governance structures, and current needs of the community that informed the design of our analysis including the scale at which we presented our results (Lacher et al., 2019b).

2.3 | Scenario development

Scenarios were developed by the stakeholder participants in two scenario-development workshops held in August 2016. Based on recommendations from our core advisory group, we held two workshops, each representing counties within either the Shenandoah Valley or the Piedmont in order to more effectively capture the distinct political views of each county group. Following a deductive-style two-axis matrix approach (sensu McBride et al., 2017), we directed participants, first individually then through group consensus, to identify what they believed to be the two most impactful yet uncertain drivers of land use change. We then asked the participants to define the extreme poles of those two drivers. By crossing these polar drivers, we arrived at four distinct scenarios for which participants created narrative descriptions of how they would envision life in these scenarios. Following this open-ended brainstorm, we directed participants to provide specific estimates of the amount and location of land use change via a standardized worksheet (see Lacher et al., 2019b for additional details, complete stakeholder narratives, and worksheet template).

"Population Growth" and "Political Will" emerged as primary drivers unique to each workshop, resulting in the following four scenarios: high population growth and strategic planning (HS), high population growth and reactive planning (HR), low population growth and reactive planning (LR), and low population growth and strategic planning (LS; Figure 2). Scenarios HS and HR focused on different planning philosophies for the spatial arrangement and density of development. In HS, new developed areas are tightly concentrated near existing urban areas while new development in HR is added in lower densities following roadways resulting in higher overall developed area. Scenario LR envisioned a future where large agricultural production subsumed forested natural areas rather than human development while Scenario LS focused on natural resource protection at the expense of local economies. We also modeled a "Business-as-Usual" scenario (BAU) intended to track the existing population and policy trends.

Finally, we note that both workshops also identified climate change as a key driver of change. However, given the limited ability of regional decision makers to influence this driver and the lack of a clear mechanism for connecting climate change to land use change at the resolution and scale of our data, we ultimately chose to not include climate in the final scenarios. This does not The new development needed to support new Development focused in urban centers maintains residents spreads along roadways with increased local agriculture & a flourishing economy while parcellation increasing forest loss & fragmentation preserving the region's charismatic beauty High Population **Reactive Planning** Strategic Planning Low Population Rural population exodus & reactive zoning results Movement of younger generations from rural areas, in extractive profiteering with little being returned reduces needs for new infrastructure while strategic

FIGURE 2 Diagram displaying the differences between each scenario. The arrows depict the drivers of change and the quadrats contain summaries of the narratives used to modify transition rates

preclude future research from integrating climate change projections with our scenarios models to consider additional questions that support stakeholder interests.

to the community and ecosystem health reduced

3 | MODEL DEVELOPMENT

3.1 | Modeling approach

We used Dinamica EGO version 3.41, a platform for temporally dynamic, spatially explicit environmental modeling (Soares-Filho et al., 2002), to simulate transitions between LULC classes in the study area for the period of 50 years from 2011 to 2061. LULC change models built within Dinamica EGO fuse Markov Chain and Cellular Automata modeling concepts, used extensively in the simulation of LULC change in various contexts (Dang & Kawasaki, 2016), to estimate and project both the quantity and spatial configuration of landscape change over time. The cellular automata approach allows for the application of rules that govern the transition of each cell in a land cover raster, within the context of a surrounding neighborhood of cells. Parameters for model calibration are determined by historic trends in the composition and configuration of landscapes as measured in categorical land cover classes. Future LULC projections are based on the geographic boundaries of analysis sub-regions, an initial LULC landscape, the transition rate of land cover classes, the spatial pattern of these transitions, and spatially explicit relationships between these transitions and physiographic, environmental, and socio-economic variables (Figure 3).



planning preserves fields, forests, & family farms.



FIGURE 3 Schematic of land use/land cover change model depicting the time period used in model development (2001–2011), specific transitions between land use/land cover classes, and the three primary parameters in the context of how they are called into the model and influenced by spatial variables

3.2 | Data

3.2.1 | Land use and land cover

We elected to use data from the United States Geological Surveys National Land Cover Database (NLCD; Homer et al., 2015) over other land cover datasets (Falcone, 2015; Rollins, 2009) because NLCD provides information on the land uses of interest to our stakeholders at multiple time steps (2001, 2006, 2011) and at a resolution $(30 \times 30 \text{ m})$ appropriate for informing county-level land use planners (Pan et al., 2019; Pennington et al., 2017). We aggregated the original NLCD land cover classes into eight total classes and then selected the four "focal classes" that exhibited the greatest change in historic data and were relevant for planning efforts and ecological impacts. These focal classes are: developed, forest, grass, and crop (Table S1). The 2011 data set is the initial landscape for all projected future landscapes.

3.2.2 | Driver variables

Soil productivity (Schaetzl et al., 2012; Soil Survey Staff, 2016), slope (USGS, 2015), geology (Dicken et al., 2005; Nicholson et al., 2005), zoning (County Governments Personal Communications), transportation travel time (Virginia Department of Housing and Community Development, 2018), distance to existing protected areas (USGS GAP, 2016, Virginia Department of Housing and Community Development, 2018, Schwartz, 2015, MALPF, 2015, MD DNR, 2013a; MD DNR, 2013b, MD DNR, 2013c; MD DNR, 2013d; MD DNR, 2014; MD DNR, 2015a; MD DNR, 2015b), median income (American Community Survey Office, 2012), and population density (American Community Survey Office, 2012) represent our static variables. Distance to Developed, and distance to Open Space represent our dynamic variables. We ran a Spearman's rank correlation analysis to identify non-independence between variables and, selected the variables with stronger measured effects on LULC transitions. Two variables, zoning and population, required additional development prior to inclusion in the model.

Zoning classifications are unique to each county in our study area and represent a wide range of classification approaches that are not directly comparable to each other. Therefore, we obtained zoning data on a county-by-county basis and then standardized all the existing zones into a new, study-area-wide classification system based on relative development density (see Supplemental Section A in Data S1). To project future development growth in our high population and business-as-usual scenarios we used a logistic regression to connect the amount of development added to the population growth over the same time period at varying distances from population centers in both urban and rural areas of the study area. We did this for each of the eight sub-regions using observed land cover change between the years 2001-2011 (NLCD) and recorded population growth between 2000 and 2011 (American Community Survey Office, 2012; USCB, 2002). We then applied this relationship to past and future population projections (Forstall, 1995; MSDC, 2017; Weldon Cooper Center for

Public Service Demographics Research Group, 2017; WVU, 2017) through the JAGS program (Plummer, 2003) to determine how much development should be added to each sub-region under each scenario (see Supplemental Section B in Data S1 for detailed methods).

Variable influence is assessed using weights of evidence (WOE). WOE gives us a sense of the relative influence of underlying drivers on land use change. Because many of these drivers are socio-economic and therefore susceptible to future changes in policy, quantifying their influence on land use change is helpful for planners and policy makers in understanding impacts of decisions made now or in the future. Weights of evidence also vary by sub-region, so context remains an important consideration for their relevance to stakeholders in different subregions across our study area (further explanation in Supplemental Section C in Data S1).

3.3 | Model business as usual scenario

We modeled LULC change across the 15 counties within our study area, including a 25 km wide buffer to account for outside influences on LULC change (Figure 1). We divided counties within the study area into eight analysis sub-regions in order to preserve distinct sub-regional policies and land use change histories. Sub-regional divisions were based on Virginia's Planning District Commissions (Virginia Department of Housing and Community Development, 2018) and West Virginia's Planning and Development Councils (West Virginia Code, 1971; Figure 1). These commissions and councils are adjacent counties aggregated to create geographically and economically linked local governments. After consulting with our core advisory group and stakeholders, we reassigned three counties between subregions in the study area and five counties in the buffer to better reflect changing inter-county relationships (Figure 1).

3.3.1 | Quantifying the amount of change

We calculated reciprocal transition rates across each of the four LULC classes excluding transitions *from* development, between the years 2001–2011 (Table S2). This allowed us to capture, for example, forest changing to grass and grass changing to forest within the same time period. Based on stakeholder input, we learned that region 5 (Figure 1) has a unique industry of lumber plantations with a historic practice of clearcutting and replanting that may have resulted in higher than normal transitions between grass and forest. We therefore calculated the rate of transitions between grass and forest transition in region 5 using average transition rates for 2001-2006 and 2006-2011. We used the extrapolated population projections described earlier to inform development in the BAU scenario. The relationship of population to development is non-linear and varies depending on how urban or rural the sub-region is (see Supplemental Section B in Data S1).

Spatial configuration of change 3.3.2

We used patches, defined as contiguous sets of pixels of the same land use type, as a unit for change in LULC configuration between the years 2001 and 2011. We calculated the mean patch size and the patch size variance using the R packages "raster" (Hijmans, 2019), and "SDM Tools" (VanDerWal et al., 2014). In Dinamica, patch shape is defined by "isometry," whereby values of less than 1 result in more linear patches and values greater than 1 increase clumping. We set isometry to 2 (sensu Troupin & Carmel, 2016) for transitions to development and 1.25 for all other transitions. We applied these parameters for patch size and shape to the model to guide placement of new or expanding patches in addition to the driver variable WOE values.

Model validation 3.3.3

We validated our BAU model by evaluating its ability to project the observed 2011 landscape, using 2001 as the initial landscape. Because of the spatial stochasticity of our model, we would expect an accuracy assessment based on a pixelby-pixel comparison of landscapes to be very low. The "reciprocal fuzzy comparison method" uses a moving window approach to assess similarities between spatial patterns of LULC classes within the window across both landscapes (Hagen, 2003; Mas et al., 2014; Shafizadeh-Moghadam et al., 2017). We varied the size of this window from 0.81 to 380 km² for a total of eight replicates. At 26 km², our projected landscape reached 42% similarity with the observed and at 380 km² reached 67% similarity. These levels matched those found in comparable Dinamica studies (36%-51% similarity across the same size range in Maeda et al., 2011).

Model scenarios 3.4

Modifying the amount of change 3.4.1

To develop models representing scenarios, we altered parameters of the BAU model. Changes in transition rates

were based on the scenario narratives themselves, quantitative estimates of rates of change developed by stakeholders at the workshops for each transition, feedback from regional experts in land use and planning, and the scientific literature. For transitions between forest, grass, and crop we adjusted transition rates using multipliers for each sub-region as specified by stakeholders. For example, we only applied a positive multiplier to forest to grass transitions in regions 1 and 4 based on stakeholders identifying the Shenandoah Valley as the location of agricultural expansion in low population scenarios. The high population scenarios incorporate logistic population growth rates that are 24% higher at each timestep than those used in the BAU model. The 24% increase is based on the percent difference in 2061 population between the two most populated sub-regions in the study area (regions 1 and 2) as projected in the BAU model. The low population scenarios incorporate linear population growth rates derived directly from development increases observed between 2001 and 2011. We then applied the population growth model (see Supplemental Section B in Data S1) to calculate the appropriate total amount of development for each high population scenario. For the high political will scenarios, we again followed stakeholder feedback generated in the scenario development workshops to proportionally reduce the rate of land transitioning to developed, reflecting a reduction in total land area that would be occupied due to policies that promoted higher density through strategic planning.

Modifying spatial configuration of 3.4.2 change

We used the same patch and weights of evidence parameters in the four scenario models as we did for the BAU model. However, we adjusted the probability of transitions to developed in a given area based on distance to existing urban centers to represent the difference in strategic or reactive planning strategies (see Supplemental Section D in Data S1).

4 RESULTS

Examining LULC change across our scenarios at varying scales (study area, sub-region, county) is important for understanding and communicating the potential relevancy of the model outputs to planners and policy makers (Mayer et al., 2016). At the scale of our study area and across all scenarios, developed land increased and forest and crop decreased, however grasses did not exhibit the same generalized trend at this scale,



FIGURE 4 Graph depicting the change in area of development (in sq km) from 2011 to 2061 across the entire analysis area as projected by each of the five scenario models

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increasing or decreasing depending on the scenario. At the county scale, differences in total area, location, and spatial configuration are more apparent. The effect of grouping counties within sub-regions enabled the model to project LULC change in a manner that reflected differences in sub-regional policies and demographics while also permitting counties to "influence" their neighbors. In this way, the impacts of one county's planning and policy could affect LULC change in another. The differential modeled response of land use change by geographic scale illustrates the impact of local land use policies on top of drivers that operate at larger, regional scales. Examining differences in county-level land use change in response to large-scale drivers helps to isolate the effect of local policies on resulting land use patterns, further solidifying the potential pathways needed to achieve desired future outcomes in conservation decision making

4.1 Study area

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We masked out the 4400 km² of protected areas to focus results on areas that land use planners could actively influence. Within the study area, development area increased in all scenarios (Figure 4a). HR generated the highest increase followed by BAU, HS, LR, and LS. In all scenarios, total forest area decreased (Figure 4b). HR generated the highest loss followed by BAU, HS, LR, and LS.

Total grass area increased or decreased depending on scenario (Figure 4c). BAU generated the largest loss followed by HR and HS. LR showed the highest increase followed by LS. In all scenarios total crop area decreased (Figure 4d). HR generated the highest loss followed by BAU, HS, LR, and LS.

Counties 4.2 Т

Development 4.2.1

Development area increased for all scenarios and counties (Figure 5a). Under the BAU scenario, Loudoun County experienced the largest increase in development followed by Fredrick and Fauguier. Fauguier experienced the largest range in increases between scenarios while Rappahannock and Madison counties experienced the lowest change and smallest differences with 1 km² or less added in each scenario. For all scenarios, Fauquier experienced the highest percent change compared to development area present in 2011 followed by Frederick under BAU and HS and Culpepper under all other scenarios.

4.2.2 Forest Ι

For all scenarios and all counties, forest area decreased except in Culpeper and Madison counties which saw



FIGURE 5 Bar graphs depicting the total area in sq. km within the study area classified as each of the four tracked land use classes within each of the counties under each of the five scenarios

increases in forest under all scenarios (Figure 5b). Under BAU, Loudoun County experienced the largest decrease followed by Fauquier, Fredrick, and Albemarle. This order is repeated in HS and LS but Fauguier shows the highest decrease in scenarios HR and LR. Fredrick showed the largest range in decreases between scenarios. Loudon shows the highest percent decrease in forest under the BAU scenario followed by either Fauquier or Frederick counties which alternate in place by scenario but have values that are always within a 1% difference of each other.

4.2.3 Grass

Grass area increased or decreased by county and scenario (Figure 5c). In all scenarios, Fauquier experienced the highest increase. Albemarle experienced the second highest increase under LR while experiencing smaller increases in the other scenarios relative to

other counties. Fredrick is the only county that experiences an increase (LA, LS) or decrease (BAU, HS, HA) depending on scenarios. Frederick also experiences the largest range between scenarios. For all scenarios, Culpepper experiences the highest percent decrease followed by Rockingham except under BAU in which Frederick experiences the second highest decrease over Rockingham. In every scenario Fauquier experiences the highest percent increase followed by Orange except under LR in which Albemarle experiences a slightly higher increase than Orange.

4.2.4 Crop

Crop area increased or decreased by county and scenario (Figure 5d). In all scenarios, Greene experienced the highest increase and Loudon experienced the highest decrease followed by Fauquier County. Culpepper is the only county that experiences an increase or decrease

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FIGURE 6 Focal maps of Frederick County and Albemarle County depicting the difference between the land use in 2061 as projected by Scenario HS and Scenario HR. The circled areas highlight the differences resulting from centralized versus reactive planning measures

depending on scenario, but only by 1 km² or less in each scenario. Fauquier experiences the largest range between scenarios. In all scenarios, Greene experiences the highest percent increase. Rappahannock experiences the second highest increase under BAU and HS, but Warren experiences the second highest increase in HR, LA, and LS.

4.2.5 | Spatial patterns within counties

In addition to total area of LULC change, landscape composition is an important factor for ecosystem function and the production of services (Tscharntke et al., 2012). Therefore, we also assessed differences in the spatial configuration of LULC classes between scenarios, at the scale of counties. Because developed land was the focus for our spatial modification on the landscape, we are highlighting examples of differences in the spatial placement of new development across scenarios (Figure 6). We provide examples for two counties, Frederick and Albemarle. In Frederick County, under the HS scenario, developed land is clustered around the existing urban area of Winchester (Figure 6a), while under the HR scenario, developed land in Frederick County is scattered across the landscape with numerous smaller clusters following transportation

lines up to the northwest (Figure 6b). We see a similar pattern of developed land between these scenarios in Albemarle County, where the HR scenario model projected small pockets of development throughout, especially in the grass-forest matrix of the northwest (Figure 6c). In Albemarle, the HS scenario instead resulted in focused development near Charlottesville and Crozet, a small town in 2011 which did not expand under HR (Figure 6d).

5 1 DISCUSSION

This study is an example of scenario planning applied to an LCM that is co-developed by conservation scientists, planners, and conservation practitioners that resulted in spatially explicit land use change maps that reflect the community's local knowledge. Our LCM projected differences in the total amount and spatial configuration of LULC between all four scenarios defined by the drivers of divergent population rates and planning strategies. Beyond defining said scenario drivers, stakeholder feedback helped us define our study area, identify focal LULC classes, prioritize drivers of change and thus our model variables, reconciled how to divide the study area into analysis sub-regions, and estimated future transition rates for land use change. Because we engaged local stakeholders from the beginning of the model development process and especially while creating and defining the distinctions between scenarios that would inform our modifications, our models are better structured to provide salient information for both planners and practitioners considering the impacts of differing policies and planning strategies (sensu Cash et al., 2002).

Engagement with stakeholders revealed the importance of scale in uptake of model outputs for planning decisions. In Virginia, planning and policy decisions are made primarily at the county level (Zoning Ordinances Generally, 1950) while land use change is also influenced by decisions made at regional scales. Therefore, it was important to be able to visualize and guantify land use change at the county scale while taking larger, regional influences into account. Our model projections depict this scale issue for several counties. For example, our models projected landscapes with visibly different development patterns within Frederick County depending on planning strategy. Clarke County borders Frederick county to the East and is crossed by several transportation corridors supporting a growing number of commuters living in Winchester City (within Frederick County) while working within metropolitan Washington DC (Agarwal et al., 2021). The expectation would be that both counties experiencing increased development, but they do not.

The majority of Clarke County is zoned for agricultural use or forest preservation, with development of higher density areas confined to the immediate geographic area surrounding existing small towns like the county seat Berryville (population 4494, US Census Bureau, 2021). Clarke county is also known to enforce a number of zoning and subdivision restrictions that make conserving open space with large acreage a priority. (County Zoning Districts, 2021, personal communication with county officials). In this way, the countiy's rural character is maintained for its citizens. Conversely, Frederick County is experiencing a development boom (Agarwal et al., 2021). Centered around the regionally large city of Winchester (population 27,700, Agarwal et al., 2021) Frederick County is understood to have less zoning and subdivision restrictions and is generally an easier place, administratively, to develop in (Permitted Lot Sizes, 1990, personal communications with county planners). These differences in zoning policy have resulted in drastically different impacts on land use and thus ecosystem health between counties. As populations and the cost of living in the Washington DC metropolitan area increases in the next several decades, it is likely to continue to push people westward. Because of this, Frederick County is at a crossroads with regards to how they approach planning, with implications on rural life, agriculture, and ecosystem health. These are all elements of planning firmly within the purview of the county alone. If county planners pursue centralized development strategies, it could not only help protect the rural nature of the Appalachian foothills in the eastern portion of Frederick, it could also decrease costs associated with infrastructure development and maintenance in that area (Burchell & Mukherji, 2003; Gielen et al., 2021). It is with this in mind that the practitioners at the conservation easement authority of Frederick County have expressed interest (personal communication) in our model projections as useful information in convincing county officials to consider long-term impacts of land use change on ecosystem services in subsequent comprehensive plans. Other county governments have expressed similar interest in our models. Loudoun County contains the westward edge of Washington DC metro area sprawl and has experienced substantial growth in the past two decades, concerning citizens and planners of potential impacts on their rural identity, agricultural resources, and ecosystem services. Loudoun County is interested in understanding how this growth may impact the western portion of their county and has contacted us for information on our model projections. Warren County is situated at the intersection of four major transportation corridors and serves as the closest entry that DC residents have for the Shenandoah River and Shenandoah National Park. According

to county planners, traffic and tourism have increased, at times putting uncomfortable pressure on residents. The county is expected to see increases in applications for residential and commercial development and is interested in how our scenarios can help them plan for this as well as the siting of conservation easements along park viewsheds and riverbanks (personal communication).

Conservation practitioners can gain additional insights by comparing dynamics between counties. For example, from Figure 5 we can clearly see that land use change, especially development replacing forest, is concentrated in a small set of counties (Frederick, Loudoun, Fauquier, and to a lesser extent Albemarle). The scenarios with the smallest forest loss for these counties dwarf even the highest forest loss scenarios in the rest of the study area. Practitioners advocating for regional forest protection can use this information as quantitative support for prioritizing their conservation actions and land preservation efforts in the locations with the highest risk of forest loss. Another informative dynamic is that, when forest loss is summed across the whole study area, the high population but strategic growth scenario results in approximately the same level of forest loss as the low population but reactive growth scenario (Figure 4b). This information could demonstrate to planners that centralized development plans might effectively mitigate the impact of higher population growth on forest loss. However, this must be interpreted with two important considerations. First, not all counties undergo the same pattern. For example, in Loudoun County, the amount of development added under HS is close to the same amount added under HR. In the neighboring Fauquier County, however, the development growth under HS is nearly half that of HR. This is likely due to the centralized growth strategy in HS pulling new development away from the slightly more rural Fauqier and concentrating it in Loudoun's metropolitan edge. This dynamic is in line with studies showing spillover impacts between jurisdictions (Towe et al., 2017) and highlights a need for planners and practitioners to be open to cross-boundary collaboration to achieve their goals. Second, the lower level of loss in forest for the study area under HS compared to HR appears to be largely due to a trade-off with loss in grass where the HR and HS scenarios decrease to nearly the same level (Figure 4c). This may be of concern to practitioners advocating for grassland habitat preservation as support for birds and other species. On the other hand, the grass lost under strategic planning is more likely to be near urban areas and thus potentially containing more fragmented, lower-quality grassland habitat compared to grass lost under reactive planning.

This question of grassland habitat quality leads to another advantage of completing our LCM at the full

region scale as opposed to modeling each county individually. By modeling relationships between LULC configuration metrics that can be calculated on both current and future landscapes with measures of ecosystem function that do not follow political boundaries, we are able to project potential futures for those functions. To date, we have completed analyses like these for the distribution of five different mammal species (Cove et al., 2019) and nutrient levels in area streams (Ahmadisharaf et al., 2020). In these analyses, we projected stronger decreases in native mammal distributions and higher increases in non-native mammal distributions and sediment and nutrient loads under the reactive planning scenarios compared to the strategic planning scenarios. We have also completed an analysis on a second suite of water quality metrics using a different relationship model (Noe et al., 2022) and have provided detailed results from this work to the Rappahannock Rapidan Regional Commission, a state-chartered, multi-county planning department, to be included as a layer in their best management practices mapping tool (RRRC, 2020). We are in the process of completing further analysis to address the above question about grassland bird habitat as well as an assessment of forest habitat connectivity that could benefit practitioner groups like the multi-jurisdictional Virginia Safe Wildlife Corridors Collaborative pursuing the goal of reducing animal-vehicle conflicts and improving safe wildlife passage. Here, our LULC projections can be used to highlight areas of the landscape to prioritize for connectivity protection. Finally, in collaboration with a landscape design team we have translated our future landscape maps into altered images from viewpoints throughout the study area (Supplemental Section E in Data S1). These products, while not yet integrated into a planning program, are intended to demonstrate the impact of a scenario in a way that may be more intuitive, and thus more effective for engaging the public, than maps.

Conservation scientists are increasingly understanding the need to acknowledge human elements in their studies (Bennett et al., 2022). Scenario planning provides a framework for incorporating the human dimension by actively engaging the community in the development of science. We used scenario planning to inform the development of land change models and subsequent projected land use futures to share with regional stakeholders involved in land use planning. Beyond the maps and numbers is a higher purpose inherent in the process. That is, to generate a collective vision of the future from our stakeholders, one that represents their hopes and fears so that they and others may help develop mechanisms for achieving pathways to targeted futures (Kass

et al., 2011). In the process, we all learn about how land use change may impact ecosystem function and services and biodiversity and connect this to the socio-economic, physical, and mental well-being of the community. This work serves as an addition to a growing body of landuse scenario planning studies conducted both within the United States and globally. Numerous studies have been completed for a singular jurisdiction at the county scale and below while others operated on a regional level (Gibson & Quinn, 2017; Oteros-Rozas et al., 2015; Thompson et al., 2020). We place our work in the expanding collection of multi-scale approaches that may help address multiple audiences and questions simultaneously (Cradock-Henry et al., 2021; Kok et al., 2007; Pereira et al., 2020; Vannier et al., 2019). Each locale offers unique challenges, communities, dynamics, and requirements in order to produce work that is relevant for change. Certainly, in the development of this study, we identified a need for more examples of such work. While the idiosyncrasies of different socio-ecological systems make it difficult to directly export inferences about land use-change findings and apply them to another region, our primary drivers of development strategy and population growth are common concerns (Park & LaFrombois, 2019; Stoker et al., 2021) and the interactive dynamics our study found between our scenarios may be informative for application in other studies.

As scientists, we are experts in identifying research questions that we believe are relevant to our field. However, when conducting work with the goal of uptake in planning and policy circles, it is imperative to connect with and engage the intended audience. Ask: Who is the end user? How does governance work? At what scale are decisions made? What are the environmental, social, and economic considerations of importance in the region? How do communities differ politically? In what format is information shared and presented? What are the underlying needs and which are most urgent? What new needs may emerge over the next 5-10 years? What kind of messaging is effective? What does the social network look like-who works with who and what collaborations are successful? What data is available and how is it used? How can you improve upon what others have done without overstepping? These questions may seem overwhelming, but if the goal is actionable science, then they are necessary.

Finally, we cannot underestimate the importance of a team in order to successfully achieve uptake of interdisciplinary science such as that conducted in this study. This sort of diverse work cannot, nor should not, be the responsibility of the conservation scientists alone, but rather the product of a diverse, collaborative team with

expertise in policy, modeling, ecology, and communications. In the field of conservation science, where funding is limited, scientists are often already saddled with the burden of increasing expectations and roles, leaving little additional bandwidth for the social aspects of this work. This was one of our biggest challenges in conducting this study. While we are encouraged by positive feedback and interest from multiple stakeholders including county planners, easement authorities, and regional advocacy organizations, we still had higher ambitions for integration of our work in planning outcomes. It is our feeling that if our team had a dedicated and experienced social scientist and communications expert from earlier on in the process we would have been able to develop deeper relationships with our current stakeholders and identify additional partnerships key to integrating our work into planning. We hope that this study serves as one example for why transdisciplinary research is important as well as another model for how to conduct it. The goal is to combine diverse expertise to produce scientific knowledge that authentically applies to the needs and interests of communities worldwide.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data used to support this work is publicly available at the source cited. All relevant R code and Dinamica model files are available here-https://github.com/LacherIara/ git CLI LULC 11-16-17

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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