An Evaluation of the Climate Change Preparedness of Terrestrial Protected Areas in Maryland.

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Abstract

The rate at which the climate changes and the direction of these shifts is highly variable across the landscape. As proposed by Loarie et al. (2009), the concept of a climate change velocity (CV) adds a spatial component to the rate at which the temperature increases across the landscape. Identifying where regions will experience the most significant changes in climate conditions is highly valuable for the management of areas with high ecological and societal value, such as protected areas (PAs). To examine the relationship between climate velocity and protected areas, Loarie et al. (2009) proposes the concept of a climate residence time (CRT), which estimates the length of time current climate conditions will remain in a given spatial location before shifting. Current infrastructure design managing protected areas is outdated and may be ill-equipped to handle future changes in climate. Current work examining the relationship between protected area and the CV is relatively new, but results are promising. Here, we evaluate the climate-change preparedness of terrestrial protected areas in MD by first, quantifying the magnitude of future changes using the climate residence time, and second, evaluating their capacity to manage changes by qualitatively scoring their associated management plans for climate adaptation and/or mitigation language. This two-fold approach showed that most PAs have climate residence times less than or equal to 1.5 years and had plans with little to no language addressing climate change and its associated impacts. This suggests that PAs in MD are poorly prepared for future changes in climate. Given these results, including CVs and CRTs within PA management plans would improve a park's adaptive capacity but also signal the need for a cross-coordinated management effort that transcends different management and governance scales.

1. Introduction

The rate and magnitude at which the climate has changed in the last decade is unprecedented, with large-scale changes to the entire climate system increasing in parallel with human activity. The increased dependency on fossil fuels in the last century has altered atmospheric GHG levels and have perpetuated annual increases in global mean temperature (Feng et al., 2014). The most recent contribution to the Intergovernmental Panel on Climate Change (IPCC) assessment report by Working Group I, AR6 Climate Change 2021: The Physical Science Basis, reports that the warming threshold of 1.5˚ C will occur ten years earlier than previously assessed under current emissions (IPCC, 2021). To assess the scale of warming, the IPCC uses the Representative Concentration Pathways (RCPs) to outline four different pathways for greenhouse gas (GHG) emissions, atmospheric concentrations, air pollutant emissions, and land use scenarios for the future (e.g., RCP 4.5 is moderate emissions) (IPCC, 2021). Regardless of the concentration pathway, human dominance over the Earth system is projected to increase in line with changes to the climate system, with certain areas experiencing different rates of change (Vitousek et al., 1997; IPCC, 2021; Ackerly et al, 2010).

Not only is the climate changing faster, but where the climate will shift is also variable. As proposed by Loarie et al. (2009), the climate velocity (CV) is one such concept that adds a spatial component to the rate at which the temperature increases across space. The CV is the ratio between the rate of temperature increase and the spatial gradient of mean annual near-surface temperature (Loarie et al., 2009). This calculates the instantaneous horizontal velocity of temperature change across the landscape, deriving the km/year unit.

Identifying areas most susceptible to future changes in climate is highly valuable for management of areas with high ecological and societal value, such as protected areas (PAs). While the climate velocity can explain the rate of climate changes of shrinking and expanding climates into protected areas, calculating the duration at which climate remains in areas can be an even more valuable tool for species conservation (Brito-Morales et al., 2018; Ackerly et al., 2010). To examine the relationship between climate velocity and protected areas, Loarie et al. (2009) proposes the climate residence time (CRT), which is the time (years) for the current climate to remain in a region before shifting. The physiography of the landscape largely informs how long these climate spaces will remain in PAs (Brito-Morales et al., 2018; Loarie et al., 2009). For example, highly diverse topographic landscapes with mountainous areas have longer residence times (Carroll et al., 2017). When coupled together, the inverse relationship between climate velocity and climate residence time can provide greater insight into future climate conditions within PAs, i. e., a high climate velocity indicates a short climate residence time.

Under optimal conditions, such as a stable climate and a robust management system, PAs are a vital tool for preserving biodiversity, conserving natural resources, and promoting public use of natural areas. However, current management design of protected areas at the state and federal level is heavily outdated in mitigating and adapting to the effects of climate change (Hannah, 2008; Araújo et al., 2004). PAs that are ill-equipped to protect the species and natural resources within them are just as vulnerable as areas with no protection at all (Araújo et al., 2004; Defries et al., 2005)

Current conservation research utilizing climate velocity and climate residence time has evolved to include more species-relevant climate variables and encompasses a wider range of species tolerances. Loarie et al. (2009)'s standard-slope method to derive local climate velocities uses only a local spatial neighborhood of pixels and single climate variables (i.e., temperature and precipitation). This fails to consider the landscape's spatial variability and oversimplifies climate conditions, causing underestimations in mountainous and flatter terrain (Carroll et al., 2015; Brito-Morales et al., 2018). As part of the AdaptWest Project, Carroll et al. (2015) and Hamann et al. (2015) propose an updated climate velocity calculation method, using a multivariate distance/analog-based CV algorithm to calculate CV values. In contrast to Loarie et al., (2009), they utilize a suite of bioclimatic (i.e., species-relevant) variables across the entire extent of the landscape to output CVs with greater ecological relevancy.

Evaluating current and future changes to the climate system using climate velocity is valuable for improving the management of PAs. Current work examining the relationship between protected area and this novel approach to CV calculation is relatively new, but results are promising in informing climate-adaptive species management. Several studies assessing how CVs interact and shift across a network of terrestrial PAs globally found current temperature conditions disappearing from almost all areas and a greater number of novel climate spaces within PAs by the end of the century (Heikkinen et al., 2020; Hoffman et al., 2019). Further, Elsen et al. (2020) provides additional policy-relevant metrics to further define changing climate conditions within PAs, introducing "protection retention" as a measure to evaluate the relationship between climate spaces of current and future PAs and "protection evenness" as a metric for comparison across countries. Some effort has been made to evaluate climate velocity and PAs in the United States specifically, but research is still largely limited (Ackerley et al., 2010).

Here, we use MD as a case study for PA evaluation because of its robust PA network, ambitious climate action goals, and the increasing availability of geospatial and remote sensing products monitoring ecosystem and species-relevant information (MD iMAP et al., 2015). The Maryland Department of Natural Resources (MDNR) manages protected lands through various programs in partnership with other state and federal agencies. Despite MD's leadership in climate action and land preservation and conservation, management of protected areas for climate change could be significantly improved. This research investigates whether MD PAs are adequately prepared for future climate changes. Particularly, we evaluate the climate-change preparedness of terrestrial protected areas in MD by first, deriving their unique climate residence times to estimate the magnitude of threat for PAs and second, scoring their associated management plans for language surrounding climate change adaptation and mitigation.

2. Methods and Data

To estimate the climate-preparedness of PAs in MD, research methodology was two-fold: first, an algorithm was developed that calculated the average CV within terrestrial PAs to estimate the duration of current climate conditions (i.e., CRT). Second, documents outlining the management of these PAs were qualitatively scored for language surrounding CC adaptation and/or mitigation. The combination of quantitative and qualitative methods best illustrates the climate vulnerability of MD PAs.

2.1 Calculation of climate residence times

2.1.1 Data sources and pre-processing

Three primary datasets were used to estimate the CRT within MD PAs: (1) MD's physical and county boundary shapefile, (2) USGS Protected Areas Database (PAD-US) MD shapefile of terrestrial and marine protected areas, and (3) velocity of climate change North America grids developed by Carroll et al. (2015) and Hamann et al. (2015) as part of the AdaptWest Project. Before these datasets were input into the algorithm, they were pre-processed for quality and for the study area of interest (Figure 1).

MD iMAP is the state's GIS platform, hosting a suite of datasets, maps, apps, and tools for spatial analysis. This database includes the MD political state boundary shapefile, created from the MD county boundary layer. This boundary was created using USGS Topo Quads, county boundaries from county governments, monument points, and MD Archive historic records (MD iMAP et al., 2015). This layer was utilized in developing the CV raster layer for only MD. Additionally, this boundary was used to create the MD terrestrial PA shapefile by modifying the MD PAD-US dataset to exclude marine PAs and PAs crossing state lines.

Created by USGS and managed in collaboration with Boise State University, PAD-US is the official GIS-inventory of terrestrial and marine PAs in the U.S. PA data is compiled from federal, state, and non-governmental agencies and organizations. PAs are included in the official geospatial database if they (1) meet the PAD-US PA definition, (2) include basic attributes for each area, and (3) are polygons, not lines (USGS, 2020). PAD-US is extensively comprehensive and validated, including public, non-profit, and privately held lands that have gone through peer review and testing by data-stewards (e.g., federal data stewards such as the Bureau of Land Management) (USGS, 2020). PAs are mapped and described using over 25 attributes, one combined feature class, and five feature classes that explain the type of PA: ‘Fee’, ‘Easement’, ‘Designation, ‘Marine’, and ‘Proclamation’ (USGS, 2020) (Table 5). PAD-US data can be downloaded for each state by shapefile, the quality of which varies for each state and largely dependent on that state’s data steward. Completeness of data within that state’s PA network is measured by the degree to which all fee PAs are included and are accurate (http://www.protectedlands.net/data-stewards/). For MD specifically, the Maryland Department of Information Technology manages the MD-PA network, reporting a 90% completeness for federal and local data, and nearly 100% completeness for state PAs (http://www.protectedlands.net/data-stewards/). MD has the largest data gaps at the sub-state and private level, decreasing their total completeness of state data to only 70%. For the MD PAD-US shapefile specifically, there are 22,118 PA polygons: 18,377 classified as Easement, 3,667 as Fee, 57 as Proclamation, 14 as Designation, and 2 as combined.

The velocity of climate change grids for North America were developed by Hamann et al. (2015) and Carroll et al. (2015) in partnership with AdaptWest, a climate adaptation conservation planning database for North America. To estimate climate change velocities, they utilize a multivariate approach of 37 bioclimatic variables derived from climate at two time periods: a base-line time period from averaged monthly climate data from 1961 to 1990 and future climate projections from 10 general circulation models (GCM) averaged from 2071-2100 under the RCP 4.5 and 8.5 GHG emissions scenario (i.e., moderate and high). Using these two climate datasets, their algorithm creates an analog-based CV surface by calculating the multivariate Euclidean climate distance between a specific location and the nearest location with a similar future climate (Carroll et al., 2015). In this method, the distance between present day-locations with specific climate conditions and their future climate analogs are divided by the number of years between these two points in time. Future climate analogs were estimated from the first five axes from a principal component analysis (PCA) of 37 biologically relevant climate variables, meaning the influence of these variables over the distribution of a multitude of vertebrate species is significant (AdaptWest Project, 2015; Carroll et al., 2015; Lawler et al., 2009). Some of these include, but are not limited to, mean annual temperature, mean temperature of the warmest and cold month and their difference (continentality measure), mean annual precipitation, mean precipitation for summer and winter, growing degree days (i.e., degree-days above 5˚C), and number of frost-free days (Hamann et al., 2015; AdaptWest Project, 2015). Gridded CV layers were developed using the analog-based climate velocity method for the entirety of North America at 1-km resolution and projected in USA Contiguous Albers Equal Area Conic (USGS). For the scope of this work, this analysis utilized the CV raster calculated using forward-velocities (present to future) under the RCP 4.5 emissions scenario from 2041-2070 (Hamann et al., 2015; Carroll et al., 2015).

All data layers were first reprojected to USA Contiguous Albers Equal Area Conic (USGS) projection, replicating the coordinate reference system of the USGS MD PAD-US dataset. When re-projecting the MD iMAP boundary layer and MD PAD-US shapefile, some of the polygon geometries had to be fixed using an internal fix geometries tool. Then, this boundary was used to clip the extent of the North America CV grid to only MD CV values to create the MD-CV data layer. Since this analysis only focused on terrestrial PAs, this boundary was also used to exclude marine PAs from the MD PAD-US shapefile. A table query of the 'Marine' feature class was also done to verify its removal from the dataset. An additional 'FID' column was added to the MD-CV data layer to represent each PA and access each polygon with a unique identifier within the CRT algorithm.

The MD PAD-US dataset is a composite of shapefiles of all PA types; because we were interested in investigating all types of PAs, all polygons were combined into one MD PAD-US shapefile that encompassed all types.

2.1.2 Climate residence time algorithm

To examine the relationship between PA and CV, we evaluate the CRT for each PA using an algorithm that took the pre-processed MD-CV raster and MD PAD-US shapefile as inputs (Figure 1). As proposed by Loarie et al. (2009), the CRT (years) was calculated by dividing the diameter (km) of each PA by that PA's average CV (km/year):

$$\text{CRT (years)} = \frac{\text{Diameter of each PA (km)}}{\text{Climate Velocity of each PA } \left(\frac{\text{km}}{\text{year}}\right)}$$

Since the projection of the MD-CV dataset had an equal area projection, we derive the diameter of each PA by using the area of a circle as a proxy for calculating the area of each polygon.

$$\mathrm{r} = \frac{\mathrm{D}}{2}$$

$$\mathrm{r}^2 = \left(\frac{\mathrm{D}}{2}\right)^2 = \frac{\mathrm{D}^2}{4}$$

Here, r is the radius of each polygon, which is half the polygon's diameter or D. We square this equation to substitute this value as r^2 in order to calculate the area, or A, of each PA polygon in km^2. We then rearrange this equation to derive the diameter of each PA in km.

$$A = \pi r^2$$

$$\text{Area of PA } (km^2) = \pi \text{ x } \frac{D^2}{4}$$

$$\text{Diameter of each PA (km)} = \sqrt{\frac{4 \text{ x Area of PA}}{\pi}}$$

The area of each PA was the number of pixels multiplied the size of pixels, which was at 1 km. Once the diameters of each PA were identified, we calculated the average climate velocity for each PA using a script that computed the zonal statistics of each polygon. Particularly, it calculated the average velocity values within the zones of each MD PA. Using the diameter and average CV velocities, we derived the CRT for each PA polygon (Figure 3; Figure 5; Figure 7)

2.2 Scoring of plans for climate change preparedness

2.2.1 Collection of MD PA programs and their management plans

MD PA programs were collected from the MDNR database of land preservation programs (https://dnr.maryland.gov/land/Pages/Tracking-Acreage.aspx) and from the Maryland Department of Planning's dashboard of MD protected lands (https://maryland.maps.arcgis.com/apps/dashboards/0f3ffd3350b24b17bd3b8e1705af3df5). Multiple programs manage varying kinds of Pas, so programs were selected based on the types of PAs they manage as outlined in USGS PAD-US of feature class categories. Programs that covered a larger number of acres under their management were also prioritized for inclusion. Management plans of these programs included a variety of documents: contracts between the landowner and organization, policy documents, program manuals and implementation guidelines, grant applications, easement agreements, statues and the management plans associated with PAs.

2.2.2 Types of programs evaluated

Each program operates at varying scales and can provide protection based on environmental, economic, social, or a combination of reasons. Table 4 summarizes their scale and purpose: The Conservation Enhancement Permanent Easements Program is managed by the US Department of Agriculture's Farm Service Agency and the MD Department of Natural Resources to fund private landowners for biodiversity and ecosystem service conservation. The MD Forest Legacy program is a joint partnership between the US Forest Service and the MDNR to protect private forests within defined "forest legacy areas" for resource use, recreation, and ecological value. All iterations of Program Open Space are managed by the state under the MDNR for public recreation and wildlife and watershed protection. The Rural Legacy program is also managed by MDNR for natural resource conservation and use (i.e., agricultural farmland and forestry), with emphasis on landscape protection to discourage urban sprawl. Managed by the MD Department of Agriculture's Farm Service Agency, The MD Agricultural Land Preservation Program focuses on preserving agricultural land for food and fiber production. The MDNR in association with the National Park Service, oversees the Land and Water Conservation Fund State Assistance program, where PAs are preserved for outdoor recreation.

2.2.3 Evaluation of protected area management plans

To qualitatively score PA plans, five categories were used as the management evaluation criteria. PAs were first categorized based on the management scale, purpose for protection, and type of PA covered. Scale of management included federal and state actors such as the US

Department of Agriculture, the MD Department of Natural Resources, the US Forest Service, the MD Departmental of Agriculture, and the National Park Service. Plans were categorized for environmental purposes if they specified preservation of biodiversity, wildlife, vegetation, and ecosystem services for ecological value. Economic purposes include natural resource conservation and use, financial payback to landowners, and mitigating urbanization. Plans managing areas for social purposes cited conservation of historic sites and outdoor recreation. Types of PA covered were either Easement, Fee, Designation, Proclamation, or Combined which denotes a combination of PA types (Table 5). Multiple types of PAs could be covered within each type of program plan.

2.2.4 Qualitative scoring of protected area management plans

Specific scoring categories included extent of climate change discussion and mention of climate velocity and climate residence time. The extent of climate change discussion was split into level and detail of discussion. Based on the detail of discussion, the discussion level scores were assigned as follows:

$$\begin{array}{l} 0 - \text{None} \\ 1 - \text{Some } (< 1 \text{ page}) \\ 2 - \text{Moderate } (1 - 3 \text{ pages}) \\ 3 - \text{Significant } (> 3 \text{ pages and/or dedicated section}) \end{array}$$

Detail of discussion included explicit mention of global warming, sea-level rise, precipitation intensity, extreme event prevalence, and other climate-change induced impacts as outlined in the most recent IPCC report. The discussion scoring also included species response to climate change, such as migration and extinction. These were used as key words to search through documents, alongside “climate”, “climate change”, “disturbance”, “environmental change”, “climate resilience”. Mention of climate velocity/climate residence time was either 0 (none) or 1 (explicit). The combination of these two categories contributed to 16 possible combinations of the final climate change preparedness score:

0	– No preparation
1–2	– Little preparation
2–3	– Somewhat prepared
4–5	– Very prepared
6	– Best prepared

3. Results

3.1 Climate residence times and climate velocities

Terrestrial PAs in MD had an average climate velocity of 1.39 km/year and an average climate residence time of 1.02 years (Figure 2; Figure 3). PAs had a maximum climate velocity of 5.33 km/year and a minimum of 0.25 km/year. About 71% of PAs had CVs less than or equal to 1.5 km/year and 89% of PAs had CRTs less than 1.5 years (Table 1). PAs with CVs greater than 3 km/year were 0.3% of all PAs. Similarly, only 1.2% of PAs had CRT values greater than 3 years (Table 1). Areas with high climate velocities were located in the southern eastern shore of MD, with one PA in western MD particularly having a velocity approaching 5 km/year (Figure 4). Low CV areas were most common in northeast MD (i.e., Harford and Cecil County) and approaching western MD (i.e., Washington and Frederick County). Areas with short residence times (0-1.5 years) and moderate climate velocities (1-1.5 km/year) were most abundant throughout central and southern MD (i.e., Howard, Montgomery, Prince George’s, St. Mary’s, Charles, and Calvert County) (Figure 5). Moderate CRT values within PAs were scattered across central MD, the largest areas located in western MD and the eastern shore (Figure 5). Longer residence times were most prominent throughout the eastern shore, with some PAs having areas approaching 6-7 years dispersed throughout the state (Figure 5). The average climate velocities for Designation, Easement, Fee, Combined, and Proclamation PAs were 1.58, 1.40, 1.34, 1.60, and 1.46 km/year respectively (Figure 6). Across all PA types, there was an average of 1.39 km/year. For the climate residence times of PA types for Designation, Easement, Fee, Combined, and Proclamation, they were 0.58, 0.20, 0.39, 0.12, and 2.75 years respectively (Figure 7). The average CRT across all PA types was about 1 year. Proclamation designated areas were the only PAs that had an average CRT greater than 1 year. About 71% of Easement, Fee, and Designation PAs and 56% of Proclamation PAs had CVs less than or equal to 1.5 km/year (Table 2). Further, more than 93% of Easement, Fee, and Designation PAs all had CVs less than or equal to 1.5 years (Table 2). Less than 1% of Easement and Fee PAs had CVs and CRTs greater than or equal to 3 km/year and 3 years respectively (Table 3). Other PA types did not have CVs greater than or equal to 3km/year. For CRTs, only 3.5 and 7% of Proclamation and Designation PAs respectively had a CRT greater than or equal to 3 (Table 3).

3.2 Management plan scores

Out of all nine MD-PA plans evaluated, only three had a final score higher than 0 (Table 4). None of the management plans explicitly discussed climate velocity or climate residence time.

Across all PA plans, the highest qualitative score for climate change preparedness was 1, little preparation for climate change. Level of score 1 discussion also varied across plans (Table 4). For the MD Forest Legacy program specifically, forest stewardship management plans were created and evaluated based on a scoring guide that scores the “threat level” and environmental importance” of PAs (USFS, 2017). Within the MD Forest Legacy Program’s scoring guide, the program outlines different criteria used to assess PAs, noting the project’s support for the Biden’s administration Executive Order 14008 *Tackling the Climate Crises at Home and*

Abroad. Some of these criteria include but are not limited to economic benefits from timber productivity, amount of threatened/endangered species habitat, and presence of unique biodiversity. Despite this context, the scoring guide has climate change resiliency as an "additional consideration" for evaluation by the Forest Legacy Program's National Review Panel. Meaning, climate resiliency is an optional criterion to consider if the original national core criterion have scores too similar to each other; climate resilience scores are based on maintenance of "high quality habitat "and presence of "significant climate corridors" as outlined by the Resilient and Connected Landscapes dataset developed by The Nature Conservancy (USFS, 2017). This is the only kind of climate-change related language within the document, making this plan have a discussion score of 1 (i.e., less than 1 page).

In contrast, the Program Open Space Stateside – Easement plan has a "climate change adaptation component" included within its management, specifically using the Green Infrastructure Assessment created by the MDNR to identify PAs that are susceptible to inward wetland migration from sea level rise (MDNR 2006; MD iMAP DNR, 2011). In conjunction with other components (e.g., rare species), their combination is used to create targeted ecological areas with varying levels of importance scores. Similar to the MD Forest Legacy Program, this level of discussion also had a score of 1, but content was more detailed and approached one page.

For other plans, discussion of climate-change adaptation and mitigation strategies were implicit and can signal potential incorporation of climate change adaptation/mitigation into plans (Table 4). For Program Open Space – Local, management criteria assesses if "the quality of the area is being maintained". Additionally, within the application for landowners of the Rural Legacy program, they ask for a summary of "any threat to the resources and character of the area". Management plans within the MD Agricultural Land Preservation Foundation repeatedly commented on the protection of the "future source of agriculture products" for their sustained "productivity" and "profitability", encouraging the prevention of any threat to the land that would impede with its resource use. Management under the Land and Water Conservation Fund State Assistance Program is supported by the Endangered Species Act, National Environmental Policy Act, and Executive Order 12898 – Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations. Analysis guided by these policies could investigate potential climate-changed caused "endangerment of critical species habitat" and "areas of large environmental injustices".

Respective management plans under the Conservation Reserve Enhancement Program for Permanent Easements and the Maryland Environmental Trust Conservation Easement Program had neither explicit nor implicit climate change discussion.

For other categories, types of PA covered, and purpose of protection were more consistent. All management plans cited environmentally related reasons as either their primary or secondary purpose for protection. Both economic and social based purposes were included in 56% of plans as reason for protection. The most common type of PA managed was Easement, with more than half of plans focused solely on easement PAs.

4. Discussion

This two-fold analysis showed that not only do most PAs have climate residence times less than or equal to 1.5 years, but management of these areas have little to no language addressing climate change and its associated impacts. This implies that terrestrial PAs in MD are not prepared at all to handle future shifts in climate, as most PAs have transient climate residencies and minimal design infrastructure managing for climate change mitigation and/or adaptation.

However, many of the implicit language within the management plans of PAs has the potential for extension into climate-related planning. For Program Open Space – Local specifically, management focused on preserving "future quality of the area" could be extended to climate change, arguing that future changes in climate change could significantly degrade quality of PA. Similarly for applicants of the Rural Legacy Program, human-caused climate change can be justified as a significant "threat to the resources and character of the area", especially within the context of the most recent IPCC report (IPCC, 2021). Additionally, current language used is optional and generalized, undermining the scale at which climate will impact PAs. Further, lack of climate change discussion is common across environmental and species planning, with most plans having little to no plan to adapt to or mitigate future changes (Hannah, 2008; EPA, 2008; Arújo et al., 2004).

There are many socio-ecological implications for shorter climate residencies across terrestrial MD areas. First, movement of current climate conditions outside of regions means novel climate spaces will likely shift into new PAs in 1 to 1.5 years. Climate is a strong dictator of species distribution and abundance, primarily governing a region's biodiversity (Pacala &

Hurtt, 1993; Burrows et al., 2014; Hijimans and Graham, 2006; Araújo and Pearson 2005). Thus, species survival is highly dependent on their respective climates, even more so for species that are reliant on the infrastructure of protected areas for survival. Given the inverse relationship between climate velocity and climate residency, PAs with high climate velocities and short residence times may have harmful impacts towards the species diversity of regions and require more specific species adaptive management for these areas. Transient climate conditions may also disrupt well-established natural resource systems, potentially impacting the productivity of woodland and agricultural areas across the state. Future warming projections is well-documented to impact cropland productivity and cause wide-scale crop and woodland mortality (Steele et al., 2018; Lee and Summer, 2015; Michaelian et al., 2011). In tandem with shifting climate spaces, resource yield could decrease, or increase, dependent on the vegetation (Steele et al., 2018). Second, PA boundaries are static; if species are moving poleward to track shifting climate spaces, initially designated areas may no longer hold species conservation value. In response to a warming climate, large-scale shifts in species distribution are well-documented (Jansen et al., 2007; Parmesan, 2006; Pacifici et al., 2017; Brito-Morales et al., 2018). This is because species migration is the most optimal tool for survival, as other mechanisms such as evolution, are too slow to track contemporary and future rates of warming. (Loarie et al., 2009). PAs are well-renowned for their successes in biodiversity conservation (Dinerstein et al., 2020; Butchart et al., 2012). However, species following shifting climate spaces outside of PAs have the potential to cause second-order effects across ecosystems, productivity of agricultural land, and availability of park space (Loarie et al., 2009; Hamann and Aitken, 2013).

4.1 Limitations

There are a few limitations to this research that impact the results of the work. First, there were many inconsistencies and gaps within the data sources that potentially affected the results. PAD-US Version 2.1 has significantly reduced prior gaps in PA data through the improved inclusion of local government lands and the newly integrated Census American Indian/Alaskan Native Areas dataset (USGS, 2020). However, the MD PAD-US dataset is only around 70% complete; this analysis may be missing PAs with potentially significant CRT and CV values. Second, given the scope of this project, this work only investigated emissions under the RCP 4.5 emissions scenario. Future research should evaluate CV and CRTs against different RCPs. More recently, the Shared Socioeconomic Pathways (SSPs) are one set of projections that have been incorporated into climate modeling in preparation for AR6 (Riahi et al., 2017). Unlike the RCPs, the SSPs incorporate demographic and economic variables such as population growth and sustainable development into emission scenarios to account for the future uncertainty in human activities (Riahi et al., 2017). Utilizing SSPs in CV and CRT calculation can provide valuable insight into the underlying socioeconomic factors impacting climate and better predict future estimates. Third, climate residence times were derived based on an approximation of the polygonal area of the PA. Research replicating this analysis using a non-equal area projection need to determine alternate methods of deriving diameter for each PA. This could potentially alter the range of values for climate residence times. Fourth, and most significant, these results do not provide insight into individual species movement or climate tolerances (Loarie et al., 2009). Despite the CV dataset being derived from species-relevant climate variables, this work cannot be solely used for specific species conservation, but rather can be supportive of determining potential species-level impacts.

4.1 Next Steps

Incorporating climate velocity and climate residence time estimates into protected area creation and adaptive management is a viable solution to address shifting climatic envelopes. Some research has already been done to incorporate climate velocity specifically into PA design (Dalmau et al., 2021; USGS, 2020; Stralberg et al., 2020). Dalmau et al. (2021) identifies slow velocity and longer residence time areas as potential climate refugia for species. Identifying areas under these conditions can be a powerful tool for conservation, as climate conditions and their associated organisms remain relatively consistent (Brito-Morales et al., 2018; Dalmau et al., 2021). Inclusion of these estimates into planning can also address species movement and the static nature of PAs because of their spatial and temporal dimension.

Updates to how PAs are designed and managed is critical, particularly reworking the infrastructure to cut across different management scales and facilitate coordination across programs. The availability of peer-reviewed, policy relevant, and highly validated climate science is unprecedented. Despite these advances, some management plans have not been updated since 2006 (e.g., Program Open Space). Furthermore, many of these programs managing PAs work independently of each other and are housed in a multitude of agencies and organizations. Future management could use these results to create a planned coordinated response addressing the different types and purposes of PAs to create a multi-network consortium of terrestrial PAs. Management should also be collaborative across the federal, state, regional, and local level as shifting climate spaces will be a transboundary issue.

Including more explicit species datasets into this framework can provide species-relevant CV and CRT results that are more valuable for PA planning. The CRT does not reflect individual species niches. Bioclimatic variables were chosen based on a suite of multiple species, and thus cannot be applied for individual species management. Future work should include more relevant biotic datasets to calculate species tolerance for climate residence times (e.g., Maryland Biodiversity Conservation Network (BioNet) dataset and/or USGS Gap Analysis Project).

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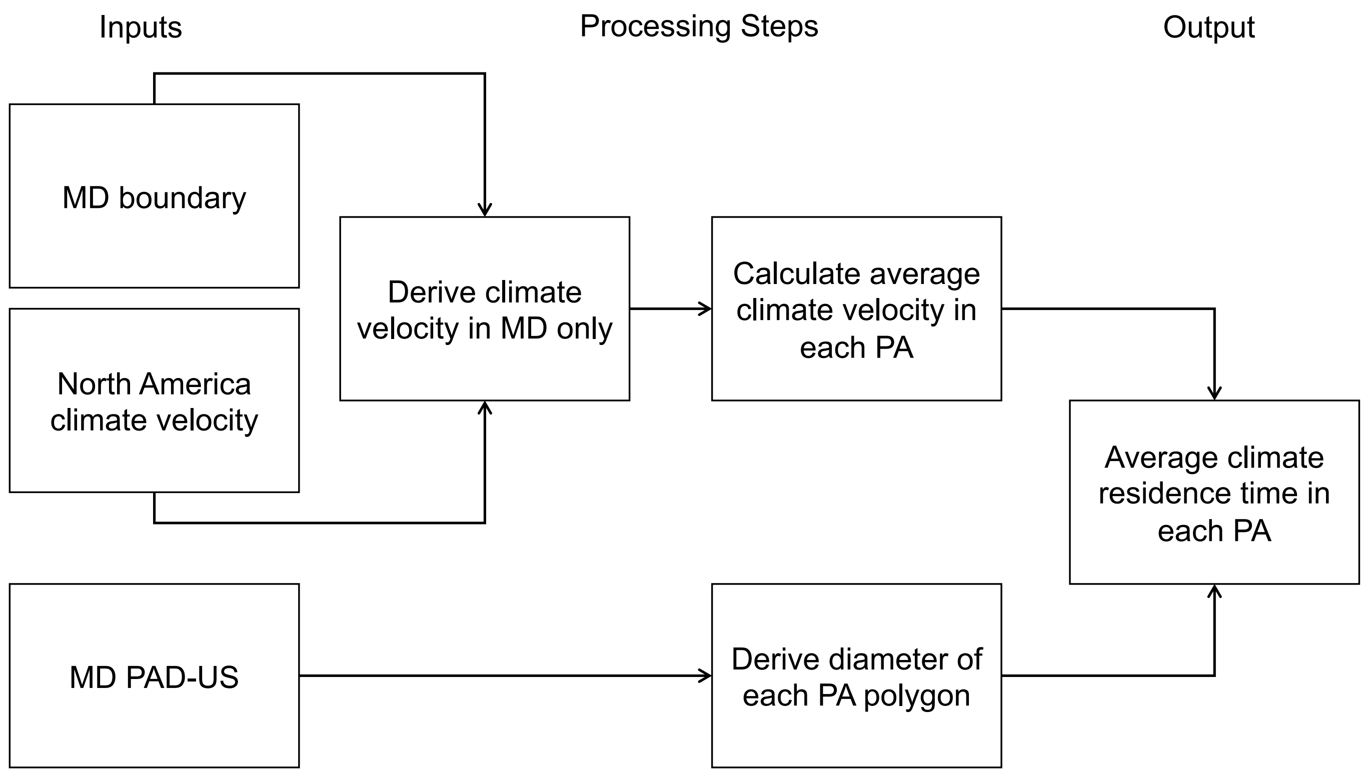

Figure 1. Flowchart summarizing workflow of algorithm. Data inputs are from the MDNR, the AdaptWest Project (2015), and USGS PAD-US (2020) respectively.

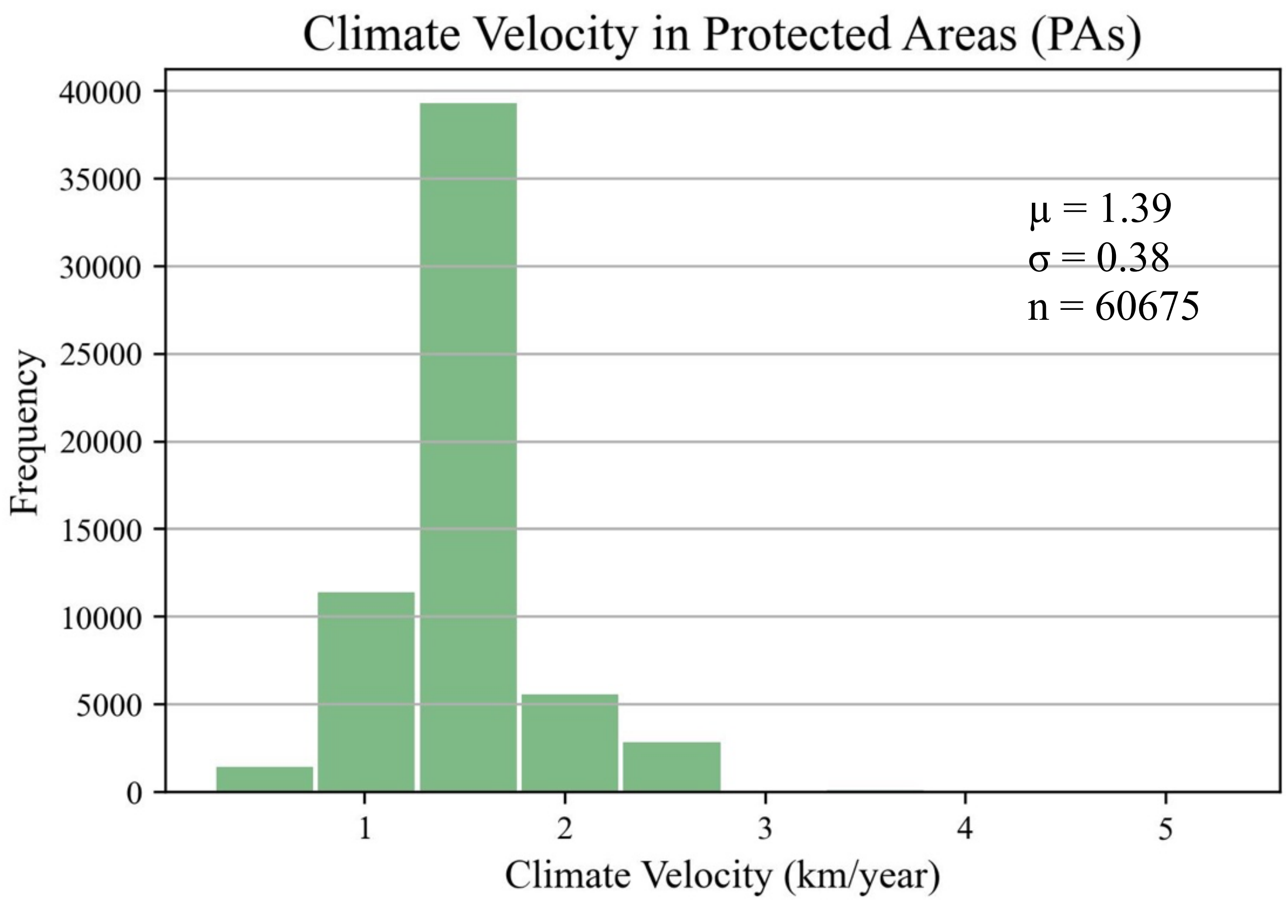

Figure 2. Weighted-area histogram of average climate velocities (km/year) for each terrestrial protected area in Maryland (MD) for 2041-2070. MD terrestrial PAs had an average climate velocity of 1.39 km/year with a standard deviation of 0.38.

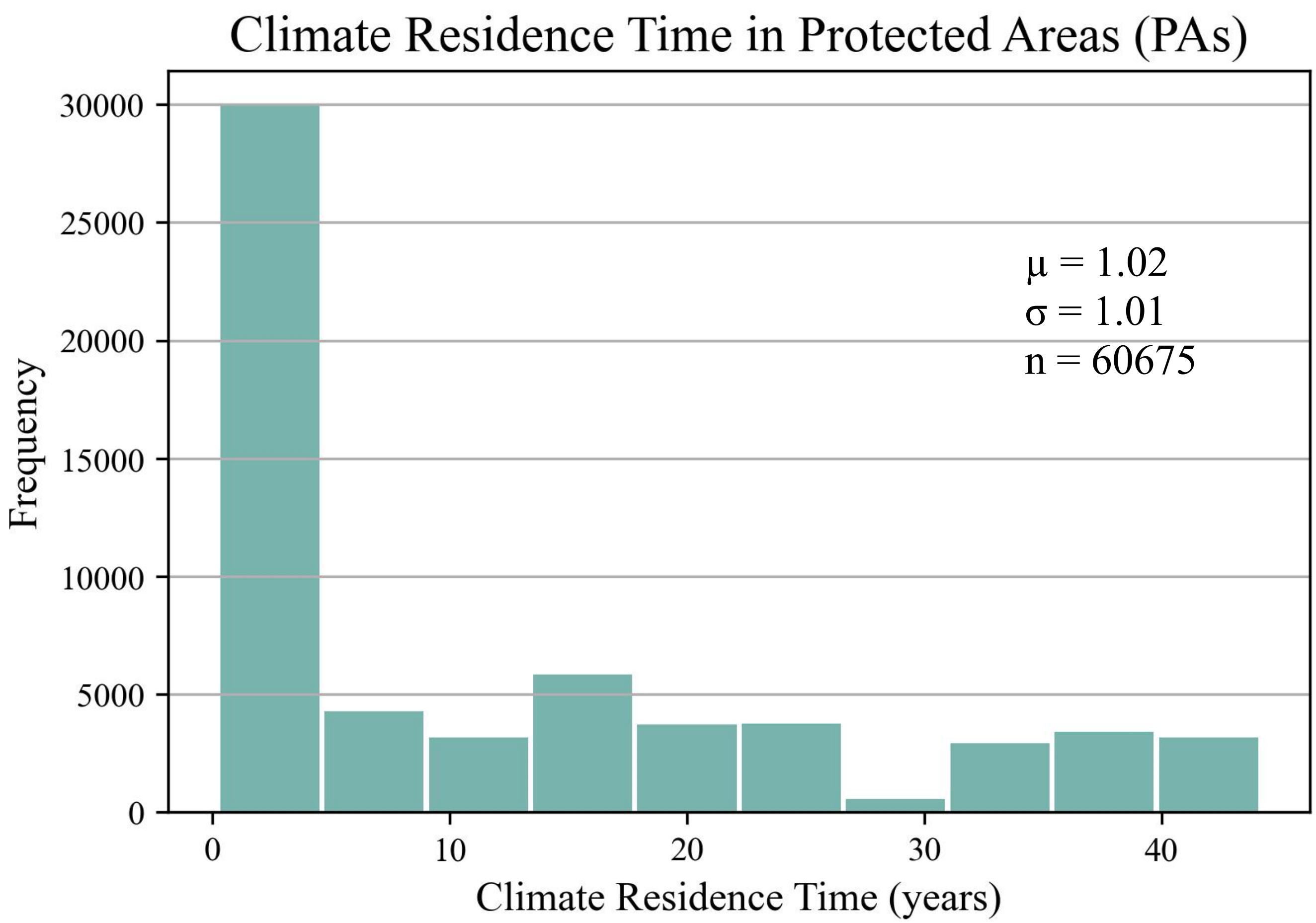

Figure 3. Weighted-area histogram of average climate residence times (years) for each terrestrial protected area in Maryland for 2041-2070. MD terrestrial PAs had an average climate residence time of 1

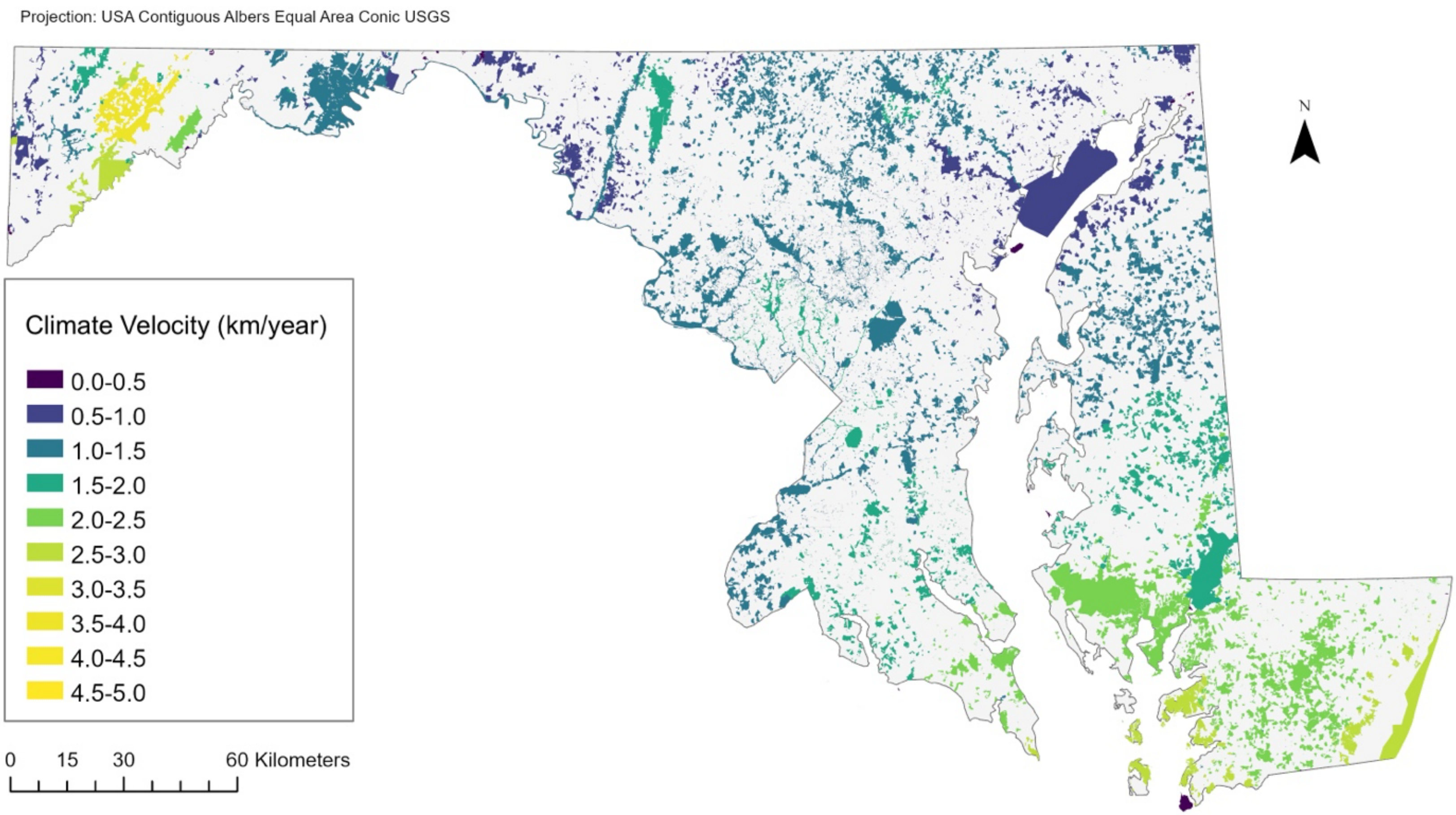

Figure 4. Map of average climate velocities (km/year) for each PA in MD for 2041-2070. Outlier values were excluded, and values shown are weighted by area. Projection is in USA Contiguous Albers Equal Area Conic (USGS). Data is from the USGS PAD-US (2020) and AdaptWest Project (2015).

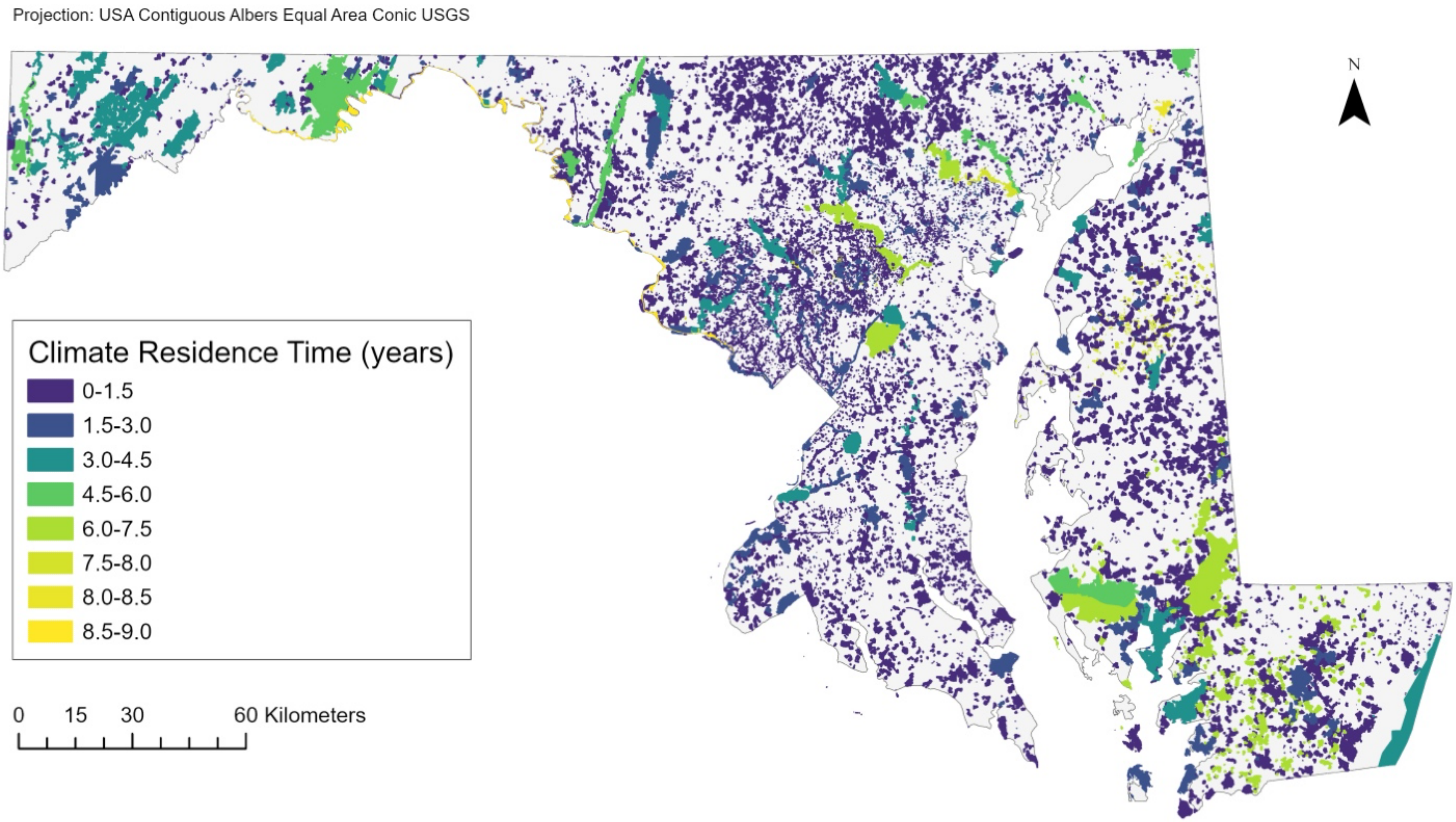

Figure 5. Map of climate residence times (years) for each PA in MD for 2041-2070. Outlier values were excluded, and values shown are weighted by area. Projection is in USA Contiguous Albers Equal Area Conic (USGS). Data is from the USGS PAD-US (2020*)* and AdaptWest Project (2015).

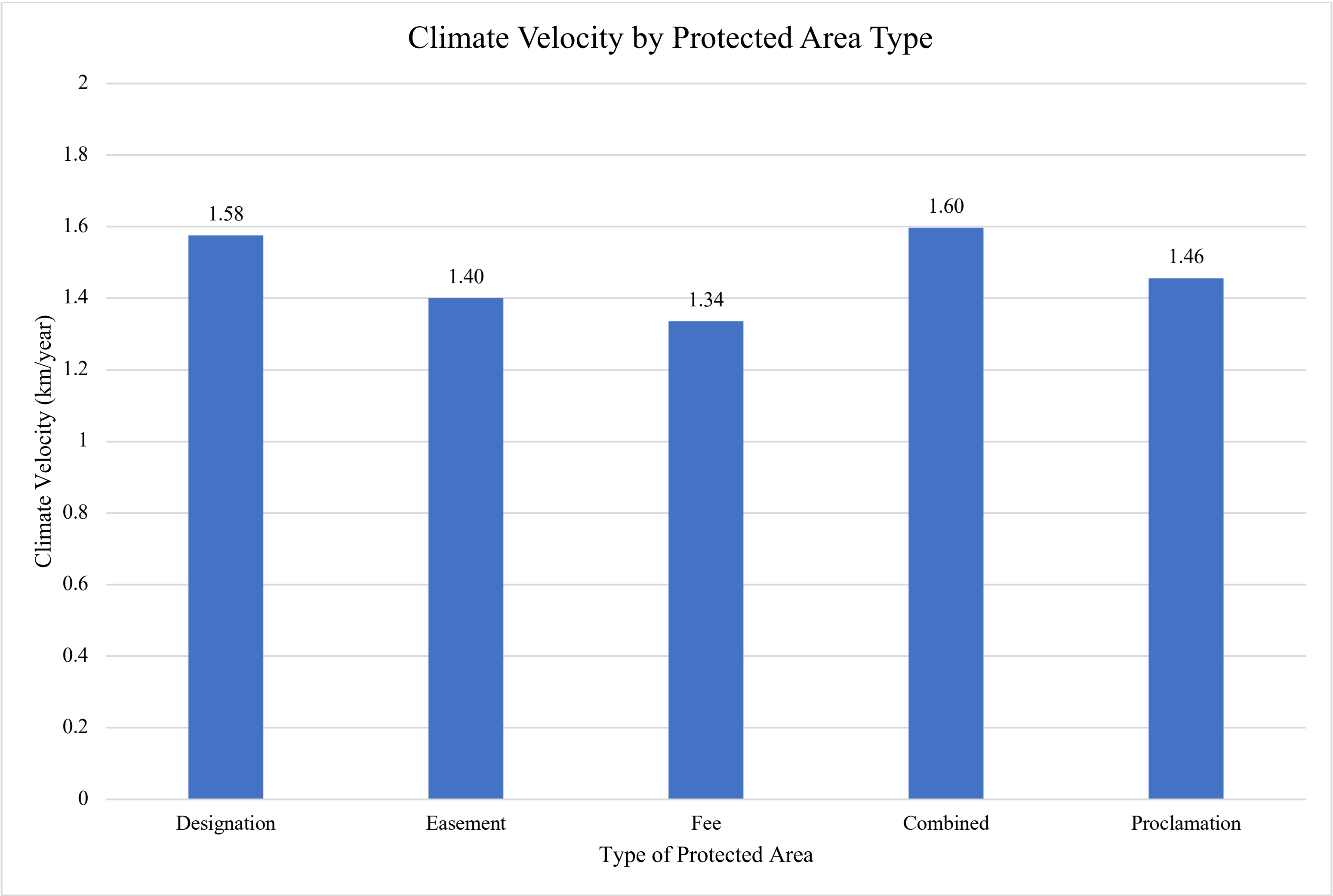

Figure 6. Average climate velocities (km/year) of each type of PA in MD for 2041-2070. Data is from the USGS PAD-US (2020) and AdaptWest Project (2015).

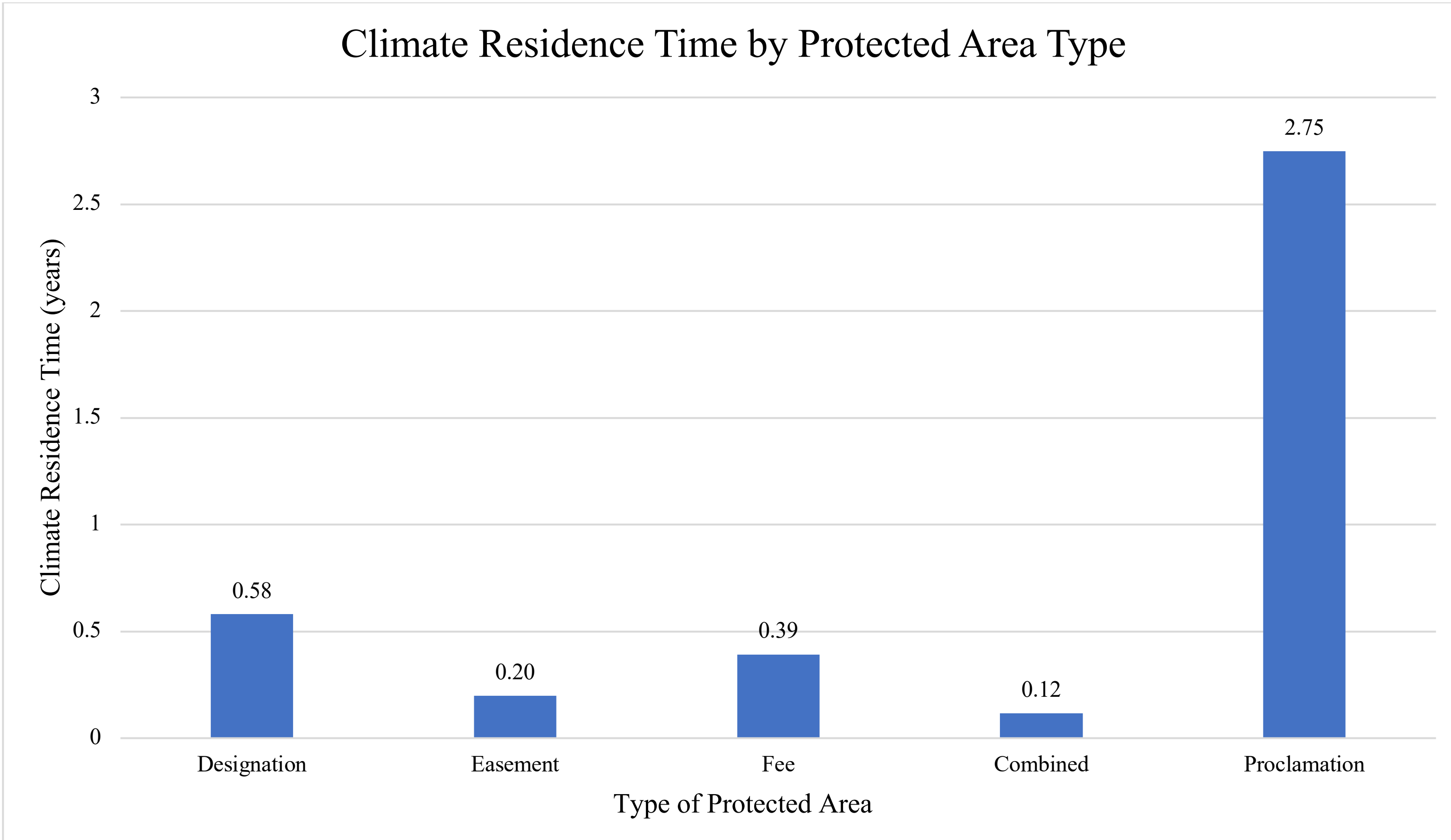

Figure 7. Average climate residence times (years) of each type of PA in MD for 2041-2070. Data is from the USGS PAD-US (2020) and AdaptWest Project (2015).

Climate Residence Time (years)	Number of PAs	Percentage of PA (%)
<= 1.5	19641	88.80
>= 3	274	1.24

Table 1. Proportion of PAs that had a CRT less than or equal to 1.5 years and greater than or equal to 3 years. There were a total number of 22,118 PAs

Type of PA	Total number of PAs	CV <= 1.5	Percentage of PA (%)	CRT <= 1.5	Percentage of PA (%)
Easement	18377	13129	71.44	18263	99.38
Fee	3667	2601	70.93	3423	93.35
Proclamation	57	32	56.14	22	38.60
Designation	14	10	71.43	13	92.86
Combined	2	1	50	2	100

Table 2. Proportion of each type of PA with climate velocities (km/year) and climate residence times (years) less than or equal to 1.5 km/year and 1.5 years respectively. There were a total number of 22,118 PAs.

Type of PA	Total number of PAs	CV >= 3	Percentage of PA (%)	CRT >= 3	Percentage of PA (%)
Easement	18377	39	0.21	47	0.26
Fee	3667	29	0.79	12	0.33
Proclamation	57	0	0	2	3.51
Designation	14	0	0	1	9
Combined	2	0	0	2	100

Table 3. Proportion of each type of PA with climate velocities (km/year) and climate residence times (years) greater than or equal to 3 km/year and 3 years respectively. There were a total number of 22,118 PAs.

Plan	Scale	Purpose	Type of PA	Extent of climate change discussion	Mention of CV/CRT	Final score
Conservation Enhancement Program (CREP) Permanent Easements	Federal/State	Environmental Economic	Easement	0	0	0
MD Forest Legacy Program	Federal/State	Environmental Economic Social	Easement	1	0	1
Maryland Environmental Trust (MET) Conservation Easement Program	State	Environmental Economic Social	Easement	0	0	0
Program Open Space (POS) Local	State	Environmental Social	Fee	0	0	0
POS Stateside – Easement	State	Environmental Social	Easement	1	0	1
POS Stateside – Fee	State	Environmental Social	Fee	1	0	1
Rural Legacy Program	State	Environmental Economic	Combined	0	0	0
MD Agricultural Land Preservation Program	State	Economic	Easement	0	0	0
Land & Water Conservation Fund State Assistance Program	Federal/State	Environmental Social	Designation	0	0	0

Table 4. Scoring of management plans of MD protected areas. Federal and state actors include USFS, USDA-FSA, MDNR, NPS, and MDA. Environmental based purposes include biodiversity and ecosystem services conservation/protection. Economic based purposes include natural resource conservation and use. Social based purposes include historic conservation and public recreation. Extent of climate change discussion ranges from None (0) to Significant (3) based on number of paragraphs and pages. Mention of climate velocity/climate residence time is explicit, 0 being no mention and 1 being mentioned. Final score ranges from No Preparation (0) to Best Prepared (6) for climate change preparedness.

Feature Class	Description	Example
'Fee'	Land owned outright by public agencies, nonprofits, or private entities.	National Forest lands owned by the U.S. Forest Service.
'Easement'	Non-sensitive conservation and open space easements provided by the National Conservation Easement Database (NCED).	Privately owned land with a voluntary conservation easement agreement in place.
'Designation'	Policy-designated areas that may overlap fee owned land, easements, or other designations.	Legislatively designated Wilderness Areas overlapping federally owned BLM, USFS, FWS, or NPS lands.
'Proclamation'	Congressionally designated proclamation, Tribal areas, military lands, and other boundaries providing context for planning or references purposes. Does not represent ownership boundaries.	National Park or National Forest boundaries congress approved for voluntary land acquisition within (boundary does not represent private, state, or locally owned/managed land inholdings).
'Marine'	Protected waters, including federal, state, and local areas in the National Oceanic and Atmospheric Administration (NOAA) MPA inventory, as well as Bureau of Ocean Energy Management (BOEM) off shore areas managed for energy and minerals.	National Estuarine Research Reserves
'Combined'	Single layer that combines feature classes.	Combinations of the 'Fee', 'Designation', 'Easement', 'Proclamation', and 'Marine' feature classes.

Table 5. Explanation of different USGS PAD-US types from USGS Protected Lands resource (protectedlands.net). Marine designated PAs were excluded because this analysis only focuses on terrestrial areas.