

PALMS Standard Operation Procedure

Estimating Protected-area Centered Ecosystems

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Introduction

The following set of methods was developed by the Park Analysis of Landscapes and Monitoring Support (PALMS) project (for a complete description of the PALMS project see Appendix A). These methods outline one approach to estimating the dimensions and spatial location of ecosystems surrounding US national parks. The results estimate a protected-area centered ecosystem (PACE) boundary at one point in time using the data and analyses available. Although ecosystems are as much conceptual as they are static and discrete entities on the landscape, there are very real boundaries to some ecological interactions. These boundaries can be estimated using theory, knowledge of local ecology, spatial data and spatial analyses (Hansen et al. 2011 included in appendix A). The user is encouraged to first review Appendix A of this document for background information, and literature supporting the development of these methods.

Parks serve a variety of functions, one of which is the preservation of natural resources and ecosystem function. Complicating parks' ability to serve this purpose is that they represent only protected (or more protected), subsets of larger ecosystems. Park natural resources often depend on the integrity of the portion of the larger ecosystem which falls outside of the jurisdiction of the park itself. Unprotected (or less protected), portions of park-centered ecosystems are often vulnerable to degradation from external sources of change. It is these unprotected portions of PACEs that are the subject of these methods. Identifying these areas is an important first step in facing the challenges of park preservation and management. The results of the following methods can focus research, monitoring, and collaborative conservation attention on these outside park areas.

As ecosystems and ecological processes are dynamic, and methods and data improve, it is likely that this exercise will need to be repeated or updated periodically. In this way the PACE boundary itself can be something of a landscape metric to track through time.

LIMITATIONS

The following sets of methods are full of subjective decisions that rely heavily on detailed knowledge of park resources and spatial data sets which describe those resources. As such, these methods are imperfect, interdisciplinary in nature and the results subject to debate and revision. That said each step is transparent and supported by considerable ecological theory (Hansen et al. in draft). The more uncertainty that surrounded specific aspects of these methods, the more conservative the authors were in developing a PACE boundary.

These methods were developed specifically for the 57 largest US national parks in the contiguous US. They were not developed for island parks, Alaska parks or small parks. That said, the general approach and many of the methods are applicable to these other parks. International borders also create a major obstacle in data availability and consistency. It is up to the user to ascertain the applicability of these methods to the park of interest and to develop solutions to these limitations.

The steps laid out in this document are meant to be a guide, allowing considerable flexibility to be modified as needed given local park resources, data and available tools. This document is meant to inspire rather than constrain its users.

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PERSONNEL

The following standard operating procedure (SOP) is largely an exercise in spatial analyses using geographical information systems (GIS). However, there are many decisions to be made along the way which require detailed knowledge of park resources and general ecological principles. Due to the interdisciplinary nature of this exercise it is not likely that any lone individual will complete this SOP in isolation. Access to a variety of park staff and subject matter experts familiar with the ecology of each park will help tremendously, in fact is necessary to produce a high-quality product. When implemented well, this mapping procedure leverages the best that expert opinion and quantitative spatial data have to offer.

There are also cases where management and political concerns surround the estimation of PACEs. The practitioner implementing these methods should be aware of these concerns and communicate and consult park management throughout implementation of this procedure. However, this SOP is meant to be a set of ecologically informed methods and things like management zones and land ownership (other than private lands), have been intentionally left out.

SOFTWARE, KNOWLEDGE AND SKILLS

The following set of instructions was written for use with ESRI's ArcGIS (v9.2), although should be achievable with prior or forthcoming versions of ArcGIS or similar software. You will need the full suite of ArcGIS desktop tools including ArcCatalog and ArcToolbox, including the spatial analyst extension. A few steps also require ArcINFO Workstation and FRAGSTATs, although there are other ways to achieve the same results for these steps using other ArcGIS software packages. A skilled GIS user will likely recognize a variety of methods that could be employed in this SOP to achieve the same end result.

The practitioner implementing this SOP should be an experienced and knowledgeable GIS user familiar with spatial datasets, projections, basic data management and have access to a host of base cartographic data layers for each park such as boundary files, digital elevation models, roads, towns, National Land cover data (NLCD), and others. The following instructions do not cover basic skills that are assumed of user such as knowledge of how to search for, download and import spatial data into a GIS from internet sources, chose a projection in which to work, reprojecting data into a common projection, datum transformations and project management in ArcGIS. As a reminder, always carefully choose a projection in which to work and reproject data from different sources into that common projection using the appropriate datum transformations. Careful project management is vital to producing high-quality results from any GIS exercise.

ArcGIS tools in each step of the following sets of instructions are invoked without specific reference to their location in ArcToolbox or ArcGIS toolbars. An experienced GIS user will likely be familiar with these tools and their use. However, if some steps are new to the user, a good way to locate tools is to use the "Search" function in ArcToolbox. The names of most tools in the document that follows are quoted so that the user can type these names in the ArcToolbox search function. The user will become familiar with the location and use of a variety of tools by the end of this SOP. The ArcGIS Desktop help menu, ArcGIS Desktop online help, and www.esri.com "knowledgebase" are also useful places to find helpful and more detailed information than is provided in this document.

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This document has been written so that any confident GIS user should be able to complete the following steps. Implementation of this SOP should not be limited to GIS professionals alone.

DATA REQUIRED

It is assumed that the user of this document has substantial knowledge of the park in question, the natural resources that the park protects, the datasets used to represent those resources, and strengths and weaknesses of these data models. The following methods are severely limited by the diversity and quality of data available for your park. The following steps are meant to be flexible and take a sufficiently coarse approach so that they can be implemented with minimal base data layers that are available nationally. If on the other hand the user has access to better data and information presented in the examples below, they may chose to work at finer spatial and thematic scales. In this way these methods can be adapted to the data and understanding available for each park.

More detail on how to access national datasets used in the following analyses are provided in each section.

Criteria 1: Watershed boundaries

Many resources such as material, energy, nutrients and organisms flow into and out of parks via waterways. The goal of this step is to include areas in the PACE that are significantly hydrologically connected to the park via surface water flow. The user may choose any watershed layer available and there are many out there with their respective strengths and weaknesses. Below is presented two simple and non-arbitrary methods using nationally available, consistent and certified datasets to identify a significant watershed area for each park.

Alternatively, a third method is outlined for users familiar with the Hydrologic analysis toolset in ArcGIS. Keep in mind that results produced by the alternative method may not match national or regional datasets even though they are produced by similar methods and data. If consistency with other watershed boundaries is important to the user, one of the first two methods is recommended.

Potential Issues

- ✓ It is sometimes a difficult decision whether to include ALL upstream contributing area in this step or some subset of upstream contributing area.
- ✓ It is also a difficult decision whether to include any downstream portions of watersheds. Motivation for doing so can include the presence of migratory fishes or invertebrates which move upstream into the park importing with them large amounts of materials and energy from downstream portions of the watershed or beyond (e.g. the ocean).
- ✓ Dams and waterfalls often provide barriers to gene flow for aquatic organisms, however they are not often effective barriers against the flow of pollutants or invasives for example. There is not often sufficient knowledge to exclude portions of a watershed because of barriers such as dams or waterfalls, however this is left to the discretion of the user and is a subjective decision to be made in this criterion.
- ✓ Not all watershed boundaries are created equal – it's always a good idea to verify the selected watershed layer using other data such as surface hydrology and elevation models for example.
- ✓ The Hydrologic unit codes (HUCs) used in the example implementation of this criterion are not “true watersheds”. They are scaled for size and their boundaries often cut across drainage boundaries especially in lower reaches of watersheds. However, the user can easily create complete watersheds by selecting all upstream HUCs from a given point and dissolving them into a contiguous polygon layer. Headwater HUC and “true watershed” boundaries should be consistent across datasets.
- ✓ Parks may be hydrologically connected to areas outside of the park via ground water that doesn't often follow surface water hydrology. This is often the case with wetlands, lakes and seeps. If ground water hydrology data is available the user may follow similar steps as those presented below to delineate areas outside the park that affect ground water inside the park.
- ✓ A similar approach may be implemented for airsheds if data exists and the park is “down wind” of significant atmospheric deposition.

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- ✓ There is a significant and difficult trade-off to be made between delineating ALL areas that impact the park in ANY way, and delineating an area that captures the strongest and most defensible impacts or ecological connections. This trade-off is most apparent in the estimation of water and airshed boundaries.
- ✓ Although upon first consideration this criterion may seem the most straight-forward to implement, it often is not.
- ✓ Be prepared for lots of discussion among folks who don't all see watersheds in the same light or have differences of opinion on what areas should be included.

The following instructions are for surface water hydrology only and should be achievable for all parks using nationally available datasets from the sources below.

Data

If your park does not have a preferred surface water hydrology and watershed data layer, the Natural Resources Conservation Service's Watershed Boundary Dataset (WBD) of hydrologic unit codes (HUCs), and the National Hydrography PLUS Datasets (NHD) are high-quality, certified data products. These data provide hydrology layers as well as a variety of related information in attached tables. You can download these data from the following sites:

NHD:

<http://www.horizon-systems.com/nhdplus/data.php>

WBD HUCs:

<http://datagateway.nrcs.usda.gov/>

Instructions

The first two steps will need to be completed no matter which method below the user chooses to implement.

1. Determine which states and NHD zones are required for your park watershed.
2. Merge appropriate state HUC and NHD files together if necessary.

Streams are called "flowlines" in NHD datasets reflecting that some are modeled.

Method 1: appropriate for most parks which exist in headwater environments and for users who wish to include all upstream contributing area to a park. This method selects all upstream HUCs which drain into the park.

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1. Using the “selection” tool, interactively select all upstream HUCs as depicted in the graphic below.

The user can select HUCs of any scale in this step and should achieve the same result for upstream areas. Note that larger HUCs (e.g. 8-digit), will be easier to work with for larger drainage areas. Note also that larger HUCs will likely include more downstream areas in the watershed boundary.

2. Decide whether to use downstream HUCs or not.
3. Once you’ve selected all hydrologically significant areas, export the selected data to a new polygon layer.
4. “Dissolve” the individual HUCs into one polygon using the Dissolve tool.
5. This polygon now represents your significant watershed area layer to be incorporated with other criteria.

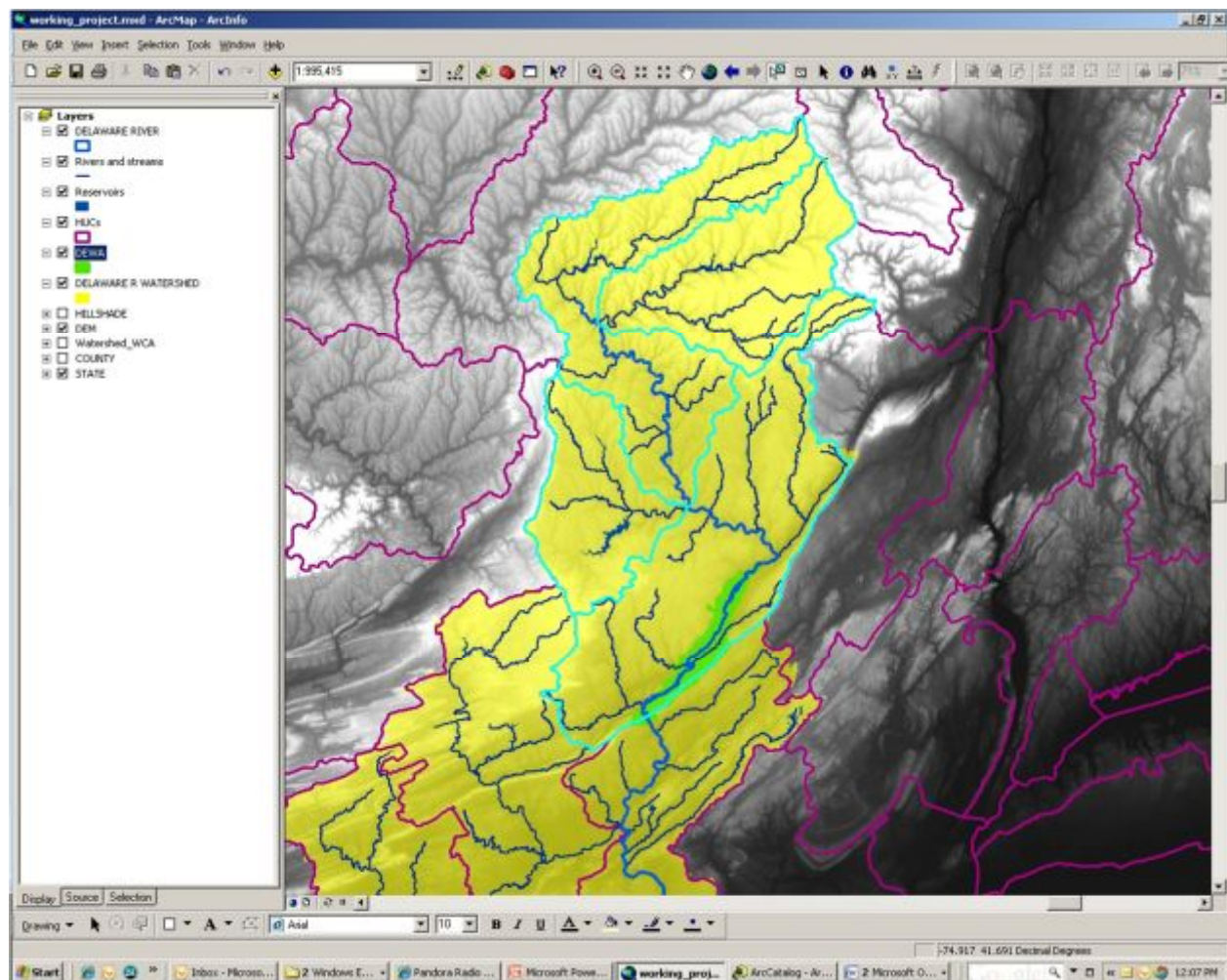


Figure 1. Example screen capture of selecting HUCs interactively

Method 2: appropriate for parks which exist in middle and lower portions of watersheds and where the user wishes to implement a non-arbitrary method of sub-setting the entire watershed to a more “manageable” size. This method uses the Strahler stream order of the largest waterway flowing through the park to select stream reaches that intersect the park and HUCs of different scales. This is done so that the larger the stream flowing through the park the larger the watershed area that will be selected.

1. At a minimum select all 12 digit HUCs which intersect the park boundary by using the “select by location” tool and export to a new shapefile.
2. Find the table that contains stream order information and “join” it to the flowline shapefile based on the ‘COMID’ field.
3. Use the “select by attribute” tool to select flowlines with stream orders 4 – 6.

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4. Use the “select by location”, “select from currently selected features in” command to subset the selected stream reaches of orders 4 – 6 to only those that intersect the park boundary.
5. Use the “select by location” tool to select 10 digit HUCs that intersect the above selected stream reaches.
6. “Export” these 10 digit HUCs to a new shapefile.
7. If a stream of order 7 – 10 intersects your park boundary repeat steps 2 thru 6 with flowlines of orders 7 – 10 and 8 digit HUCs.
8. Union the 8, 10 and 12 digit HUC files from above and uncheck the “gaps allowed” box.
9. “Dissolve” the resulting shapefile to create one polygon feature, uncheck the “create multipart features” box.
10. Decide whether there were any hydrologically significant areas left out of this criteria that the user wishes to include. Select HUCs at whatever scale that represent these additional areas and union and dissolve with the polygon from step #9 above.
11. This area now represents the watershed area to be incorporated with other criteria.

Alternative method: if the user wishes to include all upstream contributing area from the exact downstream most point in your park boundary (instead of wherever the HUC boundaries end), then use the ARCGIS Hydrologic Analysis tools, a digital elevation model and a “pour point” shapefile of your creation to model this area. Be sure to create a “depressionless” DEM and the “snap pour point” tool to create a pour point at the downstream most location(s) on waterways within your park. Detailed instructions on how to achieve this are beyond the scope of this SOP, but details can be found at <http://support.esri.com/> by searching “hydrology”.

Wrap-up

- Compare results to existing watershed layers if they exist.
- Inspect and get input from local experts.

Criteria 2: Natural Disturbance

The goal of this step is to ensure that the PACE includes the portion of the larger landscape necessary to preserve an ecosystem's natural disturbance regime and minimum dynamic area. For example, in fire dominated landscapes it's common for fires to start in lower elevation vegetation communities outside of the park and to "run" upslope into the park. In another example, in river systems that contain early succession river scour communities it's important to maintain overbank events, but avoid catastrophic flooding, that maintains these communities. Whatever the natural disturbance there are few if any protected areas around the world large enough to fully contain and preserve their natural disturbance regimes.

The following example methods are provided for a park where fire is the disturbance of interest and the data input is a layer of historical burn perimeters. The general approach could be applied to any disturbance of interest or dataset available.

Potential Issues

- ✓ Data limitations are the major hurdle here.
- ✓ If using burn area polygon data make sure that each polygon represents a unique disturbance event (i.e. multi-part polygons attributed as a single "event" as is common with tree-core data sets will not work well with these methods). However, discontinuous polygon burn perimeters as a result of "spotting" are rightfully attributed as a single fire event and will work with the following methods.

Data

For parks where fire is the natural disturbance of interest:

LANDFIRE – existing vegetation type (evt); fire regime group (frg); other fire regime data products are also helpful for comparison and helping to understand fire dynamics in your area

LANDFIRE data is available through the ArcGIS LANDFIRE data Access Toolbar

<http://www.landfire.gov/datatool.php>

or by requesting DVDs with complete datasets

http://www.landfire.gov/dataproduct_dvd.php

You can read more about all of the nationally available LANDFIRE datasets here

http://www.landfire.gov/products_national.php

Additional software

This criterion uses FragStats, a freely downloadable program that you can obtain and read more about here:

<http://www.umass.edu/landeco/research/fragstats/fragstats.html>

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Instructions

There are a multitude of fire behavior models (FARSITE for example), available which estimate fire behavior given a point of ignition, fuel conditions, weather and other factors. The objective in the implementation of this criterion is slightly different in that it takes a longer-term perspective and generalizes across a range of burn conditions. If you have a good long-term dataset of historical burn perimeters in your area, these data will generalize well across a relevant spectrum of historical conditions.

The following example takes the approach of calculating a 95th percentile large fire area and mean fire shape by LANDFIRE fire regime group and then applies that fire size and shape to the area surrounding the park. This is done to capture an area around the park that would ensure fire connectivity with the larger landscape.

The ESRI model builder model depicted below and included in this SOP package is merely one example of how to go achieve this task. The following numbered steps compliment the depicted model and the user will need both to complete this criteria (i.e. the user will have to perform the numbered steps and the model's processing steps). Each process step in the attached model is documented using the "edit documentation" function of model builder so that the user may step through each process to see what's being done and why. The user will have to modify or even rebuild the ESRI model with each park's data. The ESRI model is not necessary to produce similar results; it's only presented as an example of a labor-saving technique and to demonstrate the approach in other than narrative form. The user will want to carefully consider the natural disturbance of interest, the datasets available which describe those disturbance events and the tools useful to estimate a significant minimum dynamic or natural disturbance area around each park.

1. Load LANDFIRE fire regime group (frg) data along with the park's burn perimeter data into an ArcMap project.

LANDFIRE fire regime group data was used because it is a layer which generalizes across specific burn conditions through time and contains information about fire intensity, return interval, and spread. There are other data sources which could also be used. The following methods are not especially sensitive to this input layer; it is largely driven by historical burn perimeter size and shape.

2. LOG or otherwise transform your fire burn perimeter area data to fit a relatively normal distribution. This can be done by opening the burn perimeter attribute table and using the "FIELD CALCULATOR", then right-clicking on the 'AREA' column and using the "STATISTICS" tool.
3. Calculate a 95th percentile fire area for each fire regime group. This is the [mean AREA + 2 Standard deviations] of your LOG transformed AREA dataset.
 - a. The attached Fire Disturbance model provides an example of how to automate this step and is documented in the documentation section of each model builder process.

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- i. To view this click Edit model to open – right-click – edit documentation – “paragraph” tab

A 95th percentile large fire size was used for a Yellowstone NP burn area dataset which included the 1988 fires which are believed to have been quite large even in a long-term historical context. In other places a park's burn perimeter database may not include what are now understood to be rare, large, but historically important landscape fire events. Rather than a 95th percentile large fire size the user may decide to use the largest fire events for there is record, or even buffer the largest size if there is reason to believe that large landscape fires are important to the ecosystem in question there does not exist spatial record of these events.

The instructions that follow below assume that the attached model and all of its steps have now been completed. It picks up where the attached model leaves off.

4. Convert burn perimeters by fire regime group to grids (this is the last step of the attached model).
5. Import the grids from each fire regime group into FragStats by:
 - a. Go to FRAGSTATS – SET RUN PARAMETERS, under “Input Data Type” click the Arc Grid radio button.
 - b. Click the “Grid name” button and navigate to your Arc grid file..
 - c. Click the “Output File” button and give your output file a name and save location
 - d. Before closing the Run Parameters dialogue under “Output Statistics” click “Landscape Metrics”.
6. Use FragStats to calculate the related circumscribing circle (CIRCLE) statistic by fire regime group. Do this by:
 - a. Under the Fragstats menu click “Select Landscape Metrics”. (If this is not an option you need to go back to step 5d above).
 - b. Under the “Shape” tab select Related Circumscribing Circle (CIRCLE_?) mean, median, range, standard deviation and coefficient of variation.

The above will give an indicator of mean burn area shape, or more specifically linearity of burn as the same burn area could be produced by a compact globular fire as from a long and linear fire. This is an important distinction to make when examining connectivity to areas surrounding the park.

7. Use the following equations to calculate a cost-weight from the above area and shape information to be applied to each fire regime group. This cost-weight will be the permeability to fire of the given fire regime groups described in the LANDFIRE frg layer:

$$\text{AreaC} = 95\%_BurnedArea / (1 - \text{CIRCLE_MD})$$

$$\text{Diameter} = 2 * (\text{SQRT}(\text{AreaC}) / 3.14)$$

$$\text{CostWt} = 1 / \text{Diameter}$$

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The user may multiply the cost-weight by 1,000 (or any other number) above to get rid of some of the decimal places in this weight column. Cost-distance retains little to no real world meaning so it can be manipulated in order to ease interpretation or improve processing performance without concern for changing results. '1,000' would then become the maximum (threshold) cost-distance in the following step instead of '1'.

Another imperfect aspect of this approach is that historic fires are assigned to 1 unique fire regime group when in fact the largest events are likely to have burnt across several fire regime groups. This is done in an attempt to bring some real-world variation in how fire spreads through different land cover types and in fact many small fires are commonly contained within one unique fire regime group. With a sufficiently large dataset of historical fire events it is possible to represent some real differences in fire behavior across fire regime groups in many systems. However, in the Yellowstone National Park example there was little difference among 4 of the 5 fire regime groups, presumably as a result of the large 1988 fires that burnt indiscriminately across the landscape. This finding alone is informative and helps to parameterize the model and interpret its results.

In addition to calculating distributions of fire sizes, the attached ESRI model also combines the LANDFIRE evt layer with the fire regime group layer to be used as a fire permeability input "fire_prob_re". This step was taken in an effort to add an element of reality in how fire might spread through developed areas which are actively defended against wildfire. Said another way, this model interprets greater fire connectivity with wildland areas surrounding the park than with developed and other non-fire regime group areas (e.g. water bodies, barren classes etc). The permeabilities for non-fire regime group areas and fire regime groups containing no historical fire data are assigned in table 1 below.

8. Using the "fire_prob_re" layer produced by the attached ESRI model, open its attribute table, start editing the ArcINFO workspace and populate the "prob" field with the corresponding CostWts calculated in the previous step. This is also the step where the user will have to assign arbitrarily high weights for the non-frg land cover classes. The following are example weights used successfully in prior model runs:

Land cover	fire_prob_re -- VALUE	WT
Frg- maximum and/or no historical burn data	1 - 5	1
Water and ice	10	6
Developed	20	5
Barren and mines	30	3
Agricultural	80	4

Table 1. Suggested non-frg weights

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These analyses seem to work best when there's 1 or 2 orders of magnitude difference maximum between the weights that are calculated from historical burn data and those that are arbitrarily assigned to non-frg classes. The larger the difference between the calculated weights and the weights that are assigned to non-frg classes the more the non-frg classes will be "avoided" by the model results. This is a choice at the discretion of the user. The example weights provided in the table were used after dividing by 1000 above.

9. Use the Lookup tool on the fire_prob_re field to create a fire weight raster from the "prob" field.
10. Run a cost-distance analysis (Spatial Analysis – Distance – Weighted), using the fire_wt raster created in step 9 above as the "cost layer", the park boundary as the "Distance to" layer and a maximum distance of 1 (or 1000, or any other number used above)
 - a. Depending on how options are set, go to Spatial Analysis – Options and set both the "General – Analysis Mask" and "Extent – Analysis Extent" to the extent of the cost layer

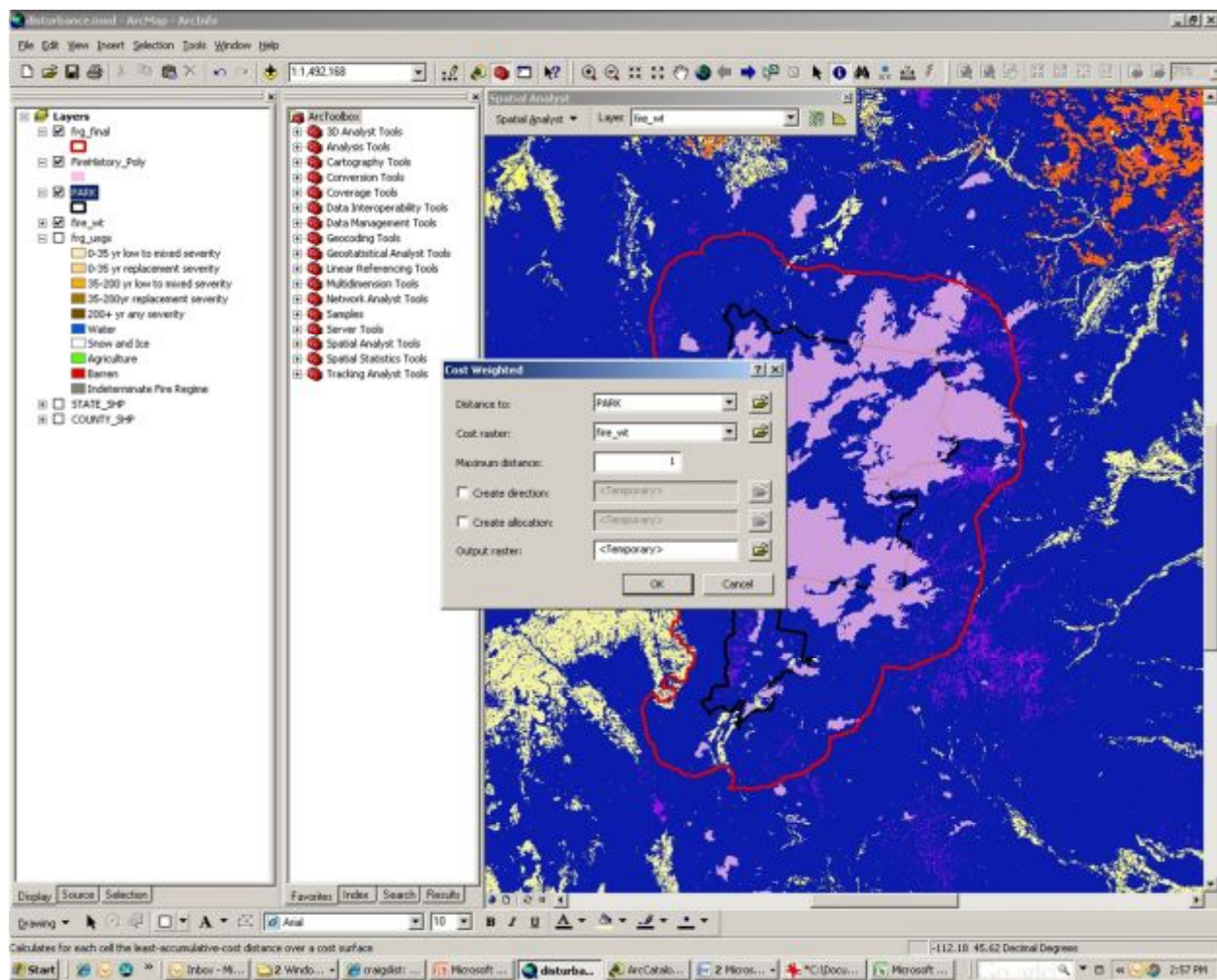


Figure 2. Example screen capture of running fire cost-distance model

11. Inspect the results closely. If there is an area of relatively homogenous and uninterrupted frg cover adjacent to the park the model should have expanded to about the same distance from the park boundary as there are records of large fires spreading across the landscape. The user can use the measure tool or visually compare historical burn area polygon 'lengths' to results as depicted in the example below:

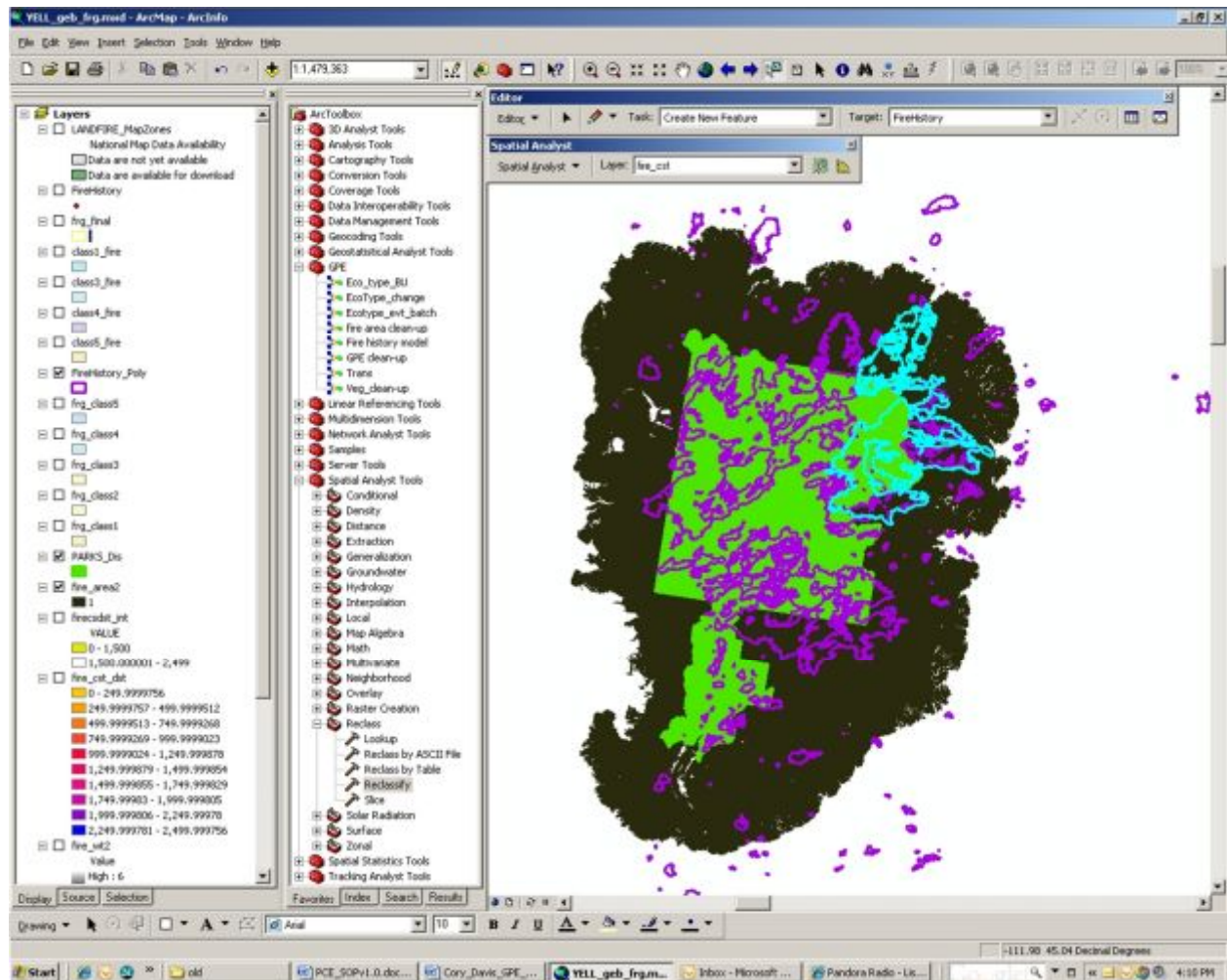


Figure 3. Comparing historical fire events to fire area boundary

Depending how much non-frg area there is immediately surrounding the park the user may have to adjust the weights in the above table and/or the threshold value. The frg-class weights will produce reasonable results, but the more non-frg classes and associated high weights that they bring, the more constrained the model will be to expand into the surrounding landscape. This is of course the point in including non-frg classes and high weights, however these model parameters may need to be adjusted for each individual park landscape. These are imperfect methods to deal with complex disturbance that's not often well-understood.

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If the park lacks a substantive fire history database and the user is familiar with FARSITE, an alternative method would be to use a routine that modeled extreme fire events under a variety of hypothetical burn conditions in FARSITE and try to develop a polygon of fire connectivity this way instead of using historic burn perimeters.

12. "Reclass" the fire cost-distance raster so that all cells = 1.
13. If there are highly irregular edges or donut holes that need to be generalized this is a good time to do so using the "expand" and "shrink" raster commands. Expanding and shrinking by about 30 – 50 cells for rasters of 30M resolution produces good results without loss of information.
14. "Convert" the raster disturbance layer to polygon to be unioned with other criteria.

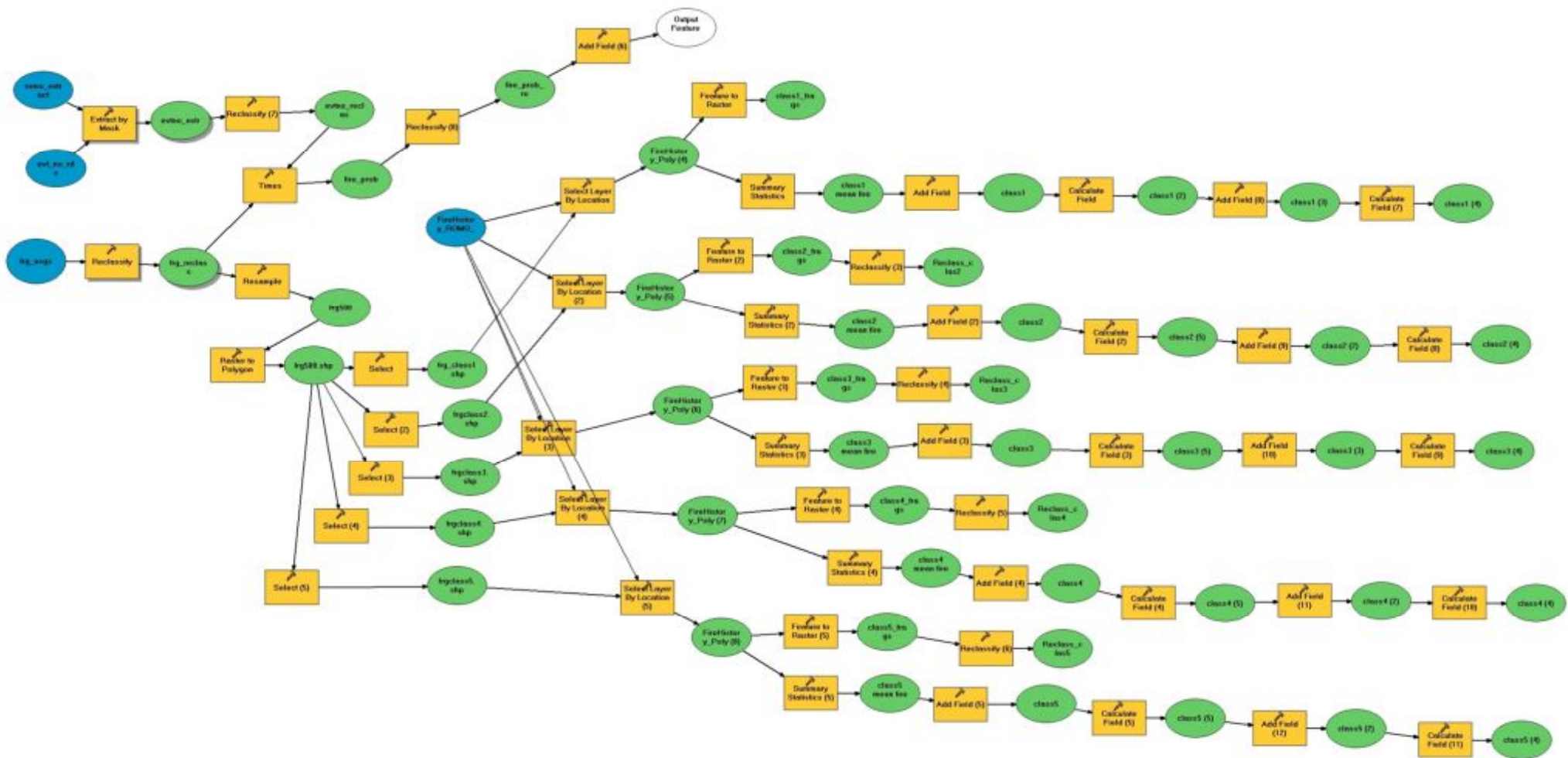


Figure 4. Example ESRI model-builder routine for calculating mean fire size by fire regime group

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Wrap-up

- Inspect results and get feedback from local experts.

Criteria 3: Crucial habitat

Many times populations of organisms that reside in the park rely on resources or populations which occur only outside of the park for either seasonal habitat, migration corridors, through metapopulation dynamics and/or via other ecological mechanisms. This captures these areas in the PACE boundary along with a conservative buffer around them that may be directly and detrimentally impacted by human activity.

Potential Issues

- ✓ Knowledge and data limitations

Data

Any information available including hand-drawn maps, narratives etc.

(See the following graphic for an example from Yellowstone National Park).

Instructions

1. Digitize whatever information is available on crucial habitat areas outside of the park for as many species as have sufficient spatial information.

This criterion was developed for use with actual animal movement or metapopulation knowledge or data, not species range maps. A range map would only be useful if it was known that the species of interest in the park was part of a larger and isolated population which was already at a minimum size as to be resilient. The idea is to incorporate areas which are vital to the survival of organisms and species populations that occur within the park, not to incorporate entire species range maps into a park's PACE.

2. "Dissolve" the layer into one polygon that encompasses all of the crucial habitat areas to be combined with polygon layers of other criteria.
3. "Buffer" this polygon layer by 5km to also include areas within which human activity may detrimentally impact this crucial habitat.
4. Add the included CUS_uppt_100 raster layer which is a national layer of protection status from D. Theobald.
5. "Extract by mask" the CUS_uppt_100 layer using the 5km buffer from above as the mask.
6. "Reclass" the CUS_100 layer by the following table 2 to isolate only developable lands from the dataset (which have a value = 1):

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Old values	New values
1	1
2 – 4	NoData
NoData	NoData

Table 2. Reclass table for CUS_uppt_100 layer

7. If there are highly irregular edges or donut holes that the user would like to generalize, use the raster “expand” and “shrink” tools on this crucial habitat layer with [Number of cells = 5], and [Zone values = 1].

Wrap-up

- Local knowledge and expert opinion can make significant contributions to this layer.
- Be conservative in this step and include all areas for which there is any information even if it's only in narrative form from a species expert referencing known locations and there is no associated spatial data available.

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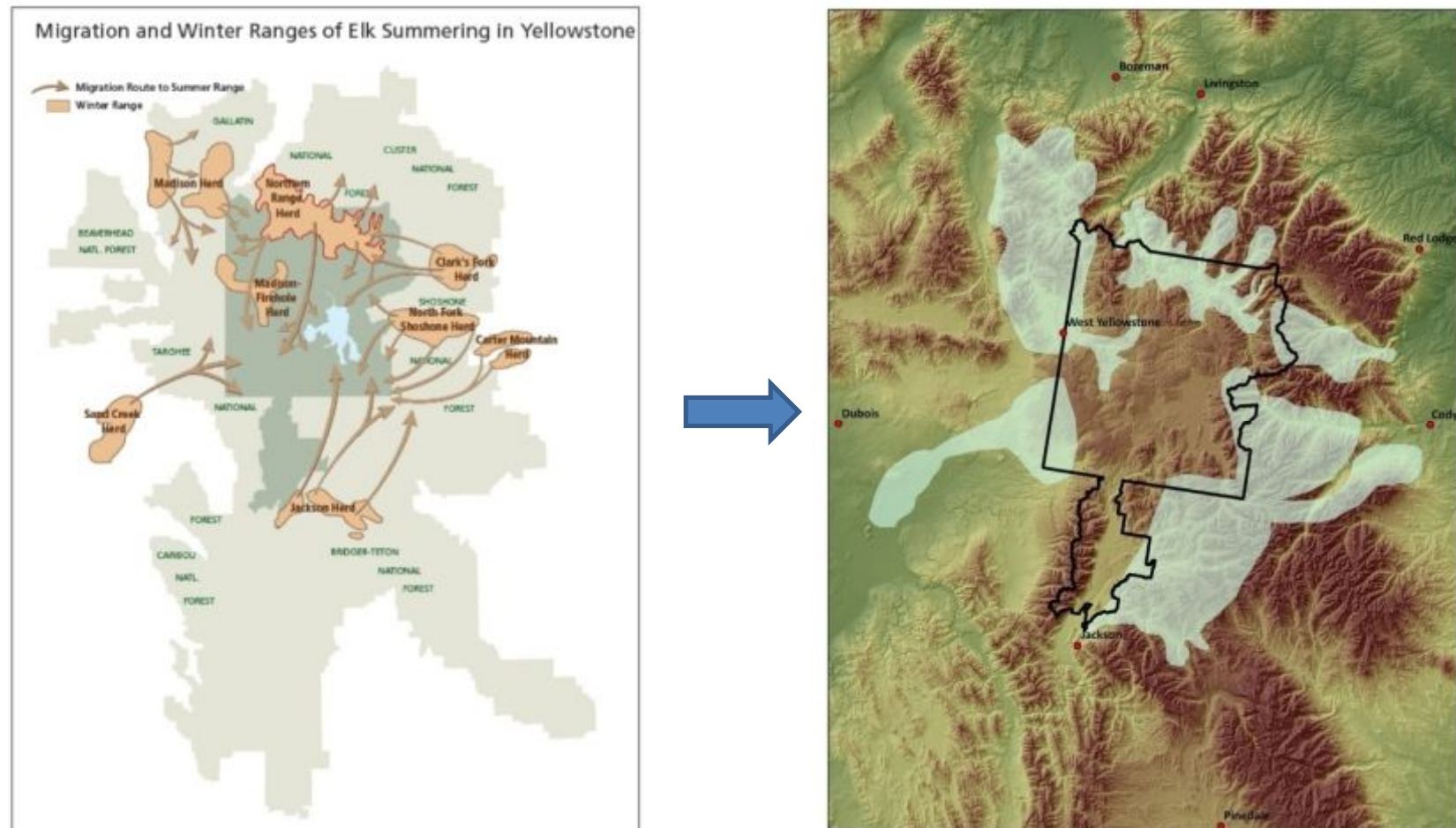


Figure 5. Example Crucial habitat criteria for Yellowstone and Grand Teton National Park

Criteria 4: Contiguous Habitat

For many populations of species that reside within parks there are outside park area effects on those populations, but not enough is known to delineate specific outside park areas as in the prior crucial habitat criterion. The contiguous habitat criterion uses ecological theory and appropriately coarse thematic analyses to capture areas outside of the park that may exhibit area effects on park populations of organisms.

This step is separated into two parts, first is a step to make species-area calculations for each park to determine a target total area, followed by a model to capture areas adjacent to the park that represent habitats most similar to those present within the park. The first step assumes that the park is currently connected to its surrounding landscape and asks the question, “If the park were to become completely isolated or disconnected from its surroundings, how much area would be needed to maintain current non-flying mammal species richness within the park-centered ecosystem?” The second step answers the question of where outside the park should be included based on the proportional representation of habitat types within the park and anything else that is known about habitat quality of park vegetation communities.

Species-Area

This step uses species-area relationships to calculate a conservative target contiguous habitat size for contiguous habitat. This step answers the question “how much?”, and the following step answers the question “where?”

Potential Issues

- ✓ For some parks a species-area approach does not work well. Below are outlined some of the cases and reasons which are known that pose problems for these methods.
- ✓ Parks often experience greater mammal sampling intensity as compared to the surrounding ecoregions in which they exist. There are cases where a park’s non-flying mammal species list includes more species than its respective ecoregion’s. Since these methods compare the proportion of species represented in a park to the “total” represented in the ecoregion, this case is problematic and these methods will not work well.
- ✓ River parks sometimes don’t work well with these methods because they often represent a great proportion of the biodiversity of a landscape in a small area (rivers and river corridors). Because these methods are comparing only species richness and river corridors are not always “available” in the surrounding landscape these methods will sometimes capture quite large upland areas in the contiguous habitat boundary when in fact many river corridor species are obligates to rivers and riparian areas.
- ✓ The smaller the park the less effect that area alone is likely having on species richness. Working with the 57 largest US National Parks in the lower 48 states there does not appear to be a minimum park size for which these methods will work. However, be forewarned that there is certainly some small size for which these methods will no longer work reliably. If the park in question is smaller than about 275 square kilometers then it might fall into this category. The user will have to examine each park’s results closely.

- o For parks smaller than 275 square kilometers, one approach could be to include your park area and species richness data in the attached Species_area.xlsx spreadsheet and recalculate the regression equation and associated slope values. This would at least ensure that the equation is applicable to parks of your size. It would not however, alleviate problems associated with confounding factors in area effects on parks of small size.
- ✓ This project did not use any data from Alaska parks, so application to parks outside of the contiguous US and/or larger than 18,295 square kilometers (the largest park used), is also not recommended.
- ✓ Ideally a species-area curve is generated by sampling in a nested fashion to isolate the effect of area alone. This was not possible given data limitations and is a weakness of this approach which introduces uncertainty to these results.
- ✓ If the user is generating a contiguous habitat area for 2 parks together then apply these steps separately for each park to ensure that the habitats in each park are adequately represented and not driven by the habitats in one park alone which happens to be larger in size. Alternatively, if both parks are small the user may achieve better results by combining the information from both parks to avoid the “small park effect” mentioned above.
- ✓ In addition to sensitivities to small park size, these calculations are also sensitive to park size relative to ecoregion size. If the park in question is small and sits within an especially large ecoregion, or straddles 2 ecoregions that combined are especially large in size the user may want to examine the results closely for signs that the calculated contiguous habitat area is being artificially inflated by this relationship. The easiest way to do this would be to look at the calculated contiguous habitat area relative to the park area and compare this proportion to others around the country. These data are included in column L “hab/park” of the “Species_area.xlsx” document included in this SOP package. Do not treat this as the only measure to compare however, as this metric itself is especially sensitive to park size.

Data

1. Certified NPSpecies non-flying mammal lists for each park.
2. WWF ecoregion data for the ecoregions that intersect each park boundary; this will include species lists through the WildFinder database. Both can be downloaded here:

<http://www.worldwildlife.org/science/data/item1872.html>

3. The attached excel spreadsheet “Species_area.xlsx” which represents a species-area curve developed for the largest US National Parks across the country and the data used to derive it.

Instructions

1. Under the main “Selection” menu in ArcGIS, use the “select by location – intersect” tool in to find the WWF ecoregions that intersect each park boundary.
2. Display only the selected ecoregions in the attribute table by pressing the “Selection” button, right-click on the ‘AREA’ column’s header and use the “statistics” function to sum the area for these ecoregions and enter this number in square kilometers (the user may need to convert to square kilometers), into the ‘Species_Area.xlsx’ excel file in the Eco_area column, row 67 of Sheet1 where it’s highlighted in yellow.
3. Use the ECO_ID field in the WWF ecoregion shapefile attribute table to find the corresponding species data in the WildFinder database ecoregions_species table.
4. Eliminate any bat species present in these ecoregions and tabulate the unique number of non-flying mammals that are present in these ecoregions.

Mammals were used because they persist in a wide-range of habitats, often require large home ranges and are well-surveyed across the country.

Birds and were not used bats because of their ability to migrate long-distances across environmental and human use gradients.

Amphibians, reptiles and other species were not used because they are not well-surveyed, do not occur in great diversity or abundance in some northern latitudes, and their populations can persist in relatively small areas.

For multiple parks and ecoregions the user will have to eliminate duplicate species that occur in each park or ecoregion in order to assemble a “unique” list.

5. Enter this number of species in the Species_area.xlsx “Eco_mam_nb” column in row 67 where it’s highlighted in yellow.
6. Enter the number of unique non-flying mammals on the park’s certified NPSspecies list in column D “park_mam_nb”, row 67 where it’s highlighted in yellow.
7. Enter the park’s area in square kilometers in column F, “Park_area” row 67 where it’s highlighted in yellow.
8. Column K “GE_area” should have updated to reflect the new target area for the park’s contiguous habitat layer in square kilometers.

More details on methods:

- *The data in the attached excel file represents species counts and areas for the 57 largest national parks in the US. From these data we derived a US Park species-area curve the parameters and regression statistics for which are in rows 61 – 65 (the chart imbedded in this spreadsheet also shows this relationship with best-fit line). The slope of this equation (0.636) represents a “mainland” relationship between species and area for US parks. This is a slope for parks that are presumed to be “connected” to their surrounding landscape.*
 - o *The low r-squared value of this equation reflects all of the confounding factors that we were not able to isolate (by dedicated specie-area sampling techniques),*

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in this relationship. Note however a significant p-value which supports that there is real pattern to variation in species richness and area of US Parks.

- o *An improved species-area relationship could be developed for each park individually given adequate data, although this is beyond the scope of this project.*
- *The relationship between main-land species richness and area versus island species richness and area (isolates), of 0.15 to 0.25 was used to calculate a US park isolate slope of '0.106' as follows:*
 - o $0.15/0.25 = 0.636/X$
 - o $X = 0.106$
 - o *A "c" value (column C, row 61), which contributes to slope, was not used because there is not a published "standard" for c-values. This is a weakness of the approach and contributes uncertainty to results.*
- *Ecoregion species and area data was used to represent expected totals for each park to constrain the model to regional conditions. However, mammal sampling effort put forth in the park relative to the ecoregion introduces uncertainty into these calculations. In many cases we expect a greater sampling effort in parks making the results of this exercise conservatively large rather than small.*
- *The graphic below shows how all of this information was used to ask the question: "If the park were to become isolated from its surrounding landscape, how much area would be needed to preserve its current species richness?"*
- *From the graphic below:*
- *#1 = park area / ecoregion area*
- *#2 = #1^{0.0636}*
- *#3 = #2^(1/0.106)*
- *The answer to the above question becomes:*
 - o *#3 * ecoregion area*

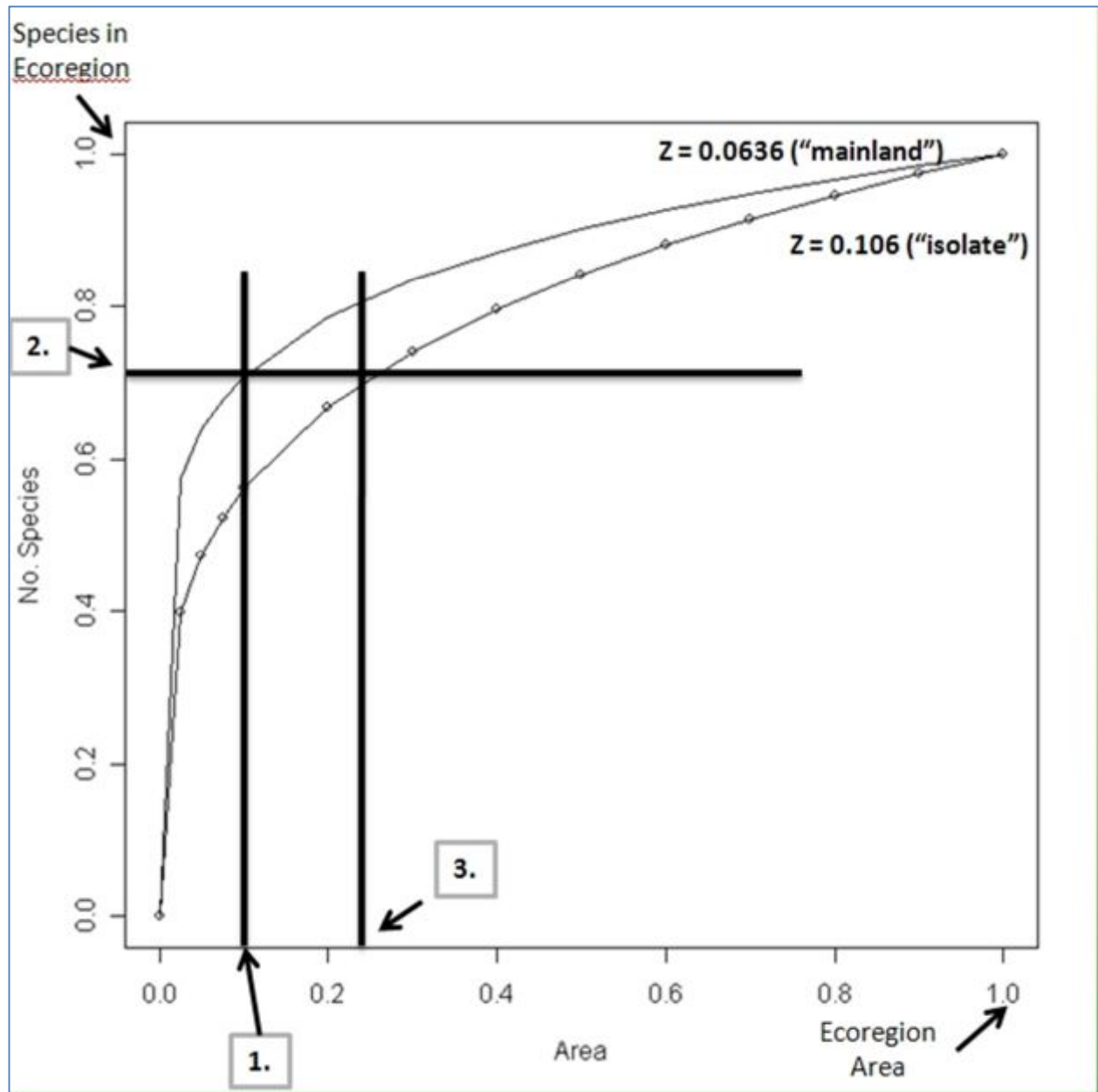


Figure 6. Species-area calculations for contiguous habitat criterion

Habitat modeling

This step uses ecological systems level vegetation community data to represent distinct habitat types in the park. Using these data it builds a model that grows into the surrounding landscape preferentially including habitat types based on their proportion of representation within the park. There are opportunities to manipulate the model to select habitats of special value or concern based on knowledge of the park and its species in this step. However, given the coarse non-

species specific nature of this contiguous habitat approach, and opportunities to include more detailed information in the crucial habitat criterion above, it is not recommended that the user manipulate too many of the habitat weights in this step. The resulting contiguous habitat area should resemble the habitats and dominance of those habitats by area as they occur in the park.

Potential Issues

- ✓ Similar to delineating ecosystem boundaries, delineating and identifying vegetation communities and/or wildlife habitats is a highly subjective endeavor.
- ✓ Not all vegetation community or land cover data layers are created equal. Many are produced from a combination of remotely-sensed and ground field plot data. Differentiating some communities with this approach can be problematic.
- ✓ Finding the appropriate thematic scale to use with these methods is something of an art. National Landcover data with its roughly 15 or fewer vegetation classes seems to be insufficient to represent variation in habitats across the landscape, whereas alliance level vegetation communities may be at a finer thematic resolution than is justified by this approach. Our experience is that roughly from ecological systems level classes to Society of American Foresters (SAF) classes are about right to be used with these methods.
- ✓ Since it's necessary to have vegetation community information for areas often far outside of the park, the NPS/USGS produced vegetation maps for parks do not usually provide the coverage necessary even though they're almost certainly of higher quality than alternative datasets. That said, it's worth looking at reported accuracy tables for each park area and comparing the data source of choice (LANDFIRE in this example case), to each park's NPS veg map especially where the NPS produced association or alliance level maps have been cross-walked to NatureServe's ecological systems used by LANDFIRE. This is becoming a more common occurrence within the NPS I&M community so check with network I&M folks to see if this has been completed or contracted to be done at each park. In the absence of crosswalks it can be difficult to compare park alliance or association level maps with ecological systems level maps without highly specialized knowledge of these methods and classification systems.
- ✓ Roughly 80% classification accuracy is to be expected with these kinds of vegetation community classification schemes and should be considered "good" for this application.
- ✓ LANDFIRE has produced classification accuracy tables for their evt layer which can be downloaded from the LANDFIRE site (www.LANDFIRE.gov).
- ✓ The cost-distance computation in Spatial Analyst works only on integer rasters and there is a maximum range of 999,999 for integer rasters sometimes requiring the user to manipulate values to work within this limitation.
- ✓ There is a 2GB size limit on shapefiles, so if the user exports the habitat layer directly to a shapefile without reclassifying as described in step 28 of this section ArcGIS will likely crash.
- ✓ For ocean parks the user will have to decide how to treat open ocean water.

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- ✓ This and the above species-area steps are the most difficult to communicate its methods and justification to others.

Data

1. LANDFIRE existing vegetation type (evt) layer for the area around each park.
 - a. (More detail about how to access LANDFIRE data is provided in the Data section of Criterion 2 above).
2. NPS/USGS veg map if available.

Instructions

1. “Mosaic” LANDFIRE region data together if the park sits at or near a border between LANDFIRE regions. The user can use the LANDFIRE Smart Assembler tool in the ArcGIS LANDFIRE Data Access Toolbar to do this, or standard ArcGIS tools.

Both the LANDFIRE Smart Assembler and the ArcGIS mosaic tools truncate the attribute table of raster layers so that in this case the important vegetation community information is lost. The user will need to reassemble this information as follows:

2. The user can either perform a standard “join” using the ‘VALUE’ field as the common field to create a temporary join between the original evt layers with complete vegetation community information and the newly mosaiced layers. Or to perform a more clean and permanent join perform the tasks in steps (3-5) below:
3. Open ArcINFO workstation and at the Arc prompt change the workspace to wherever you have your raster layer and the INFO table from the original LANDFIRE layer. Use the ‘w’ command:

```
Arc: w c:\parkdata\YOSE
```

4. Next, type in the following expression substituting specific file names for the generic ones provided in the example (“[sp]” indicates a space is necessary):

```
JOINITEM[sp] MergedEVTLayer.VAT[sp] evtinfo[sp]  
MergedEVTLayer.vat[sp] Value
```

5. Back in ArcGIS remove the evt layer and then add it back to the project and the complete attribute table should display.

[Start again here if you used simple JOIN above]

6. Use “extract by mask” to subset the evt layer to the park boundary.

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7. Open the new park_evt layer's attribute table and use the "statistics" function on the 'COUNT' field to get a total sum for 'COUNT' and write this down. As 30m X 30m pixels this number times 900 should be about equal to the area of the park in square meters.
8. "Add" a double field called 'PROP', (for proportion of total area) to the table.
9. Use the "field calculator" to make [PROP = COUNT/your sum of COUNT from above].
10. "Add" a long integer field called 'WT'.

These steps bounce back and forth between long integer and double fields to save processing time in a later step.

11. Make [WT = 1/PROP].
12. "Add" another double field called 'WT_1000'.
13. Make [WT_1000 = WT/1000].

Weights are divided by 1000 to avoid ArcGIS limitations placed on integer rasters, as well as to improve processing performance. Bear in mind that "cost-distance" retains little to no real-world meaning so these values can be manipulated without concern for changing results.

The weights in the WT_1000 field can be interpreted as permeability for the cost-distance model that will be run later. The model will expand into cells with low weights without incurring as much "cost" as those of higher weights. Said another way, the model will preferentially "select" lower weight cells. The selection comes when the model area is thresholded to the target area which was calculated in the prior species-area step.

The weights now in the WT_1000 column were generated solely based on the area that they occupy in the park. However, vegetation classes that occur in very small areas get unnecessarily high weights using this technique that will produce undesirable model results so the user must assign maximum weight values.

The user can experiment with values; it is suggested that a maximum within-park weight of '1' is assigned.

14. Under the attribute table "Options -- Select by attribute" [WT_1000 values > 1].
15. Use the "Show:Selected" button and the "field calculator" to make all selected [WT_1000 values = 1].

Now that weights are assigned to all cells within the park, comparable weights need to be assigned for vegetation communities in the surrounding landscape.

16. "Add" a new double field in the original evt layer called 'WT'.
17. "Join" the park_evt layer to the original evt layer based on the 'VALUE' field.
18. Use the "field calculator" to make [evt_WT = park_evt_WT_1000].
19. "Remove the table join", open the evt attribute table and "sort" based on the new WT field.

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The column values which = 0 represent classes that occur in the surrounding landscape but not within the park. The user needs to assign weight values to these classes too. The user can experiment with different values, however the values in table 3 below have been successfully used in model runs for other parks. Bear in mind that the higher the weight the more it will be avoided by the model:

Classes	Values	Weight
Natural vegetation not in park	2000s	3
Human disturbed, modified, managed vegetation classes (e.g. ruderal, introduced, recently logged etc.)	2000s	5
Developed general	20	7
Developed open space	21	5
Developed low intensity	22	7
Developed medium intensity	23	15
Developed high intensity	24	20
Barren	31	User's decision
Agricultural general	80	10
Agricultural Pasture/hay	81	7
Agriculture Cultivated crops and irrigated ag	82	10
Agriculture small grains	83	10
Agriculture fallow	84	7
Agriculture urban recreational grasses	85	10
Unclassified all	200s	User's decision

Table 3. Weights for vegetation community classes to be used in cost-distance analysis

20. "Start editing" the ArcINFO workspace in which the evt layer resides and modify the above class WTs according to table 3 above. Every class in the evt table should now have a value associated with it in the WT column.

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Now if the user chooses, examine the weights again and adjust any natural class weights according to understanding of their importance to the local system. Wetland and riparian classes that occur within parks are often more important to supporting species than the area that they occupy would suggest. These are often candidates to subjectively decrease their weight (increase their importance), accordingly.

Many systems have habitats that provide seasonally available resources during a time of year when resources are scarce elsewhere. These are also good candidates to subjectively decrease their class weights.

For decreasing weights a subjectively low weight of ~ 0.001 , and a subjectively medium weight of ~ 0.05 is recommended.

Adjusting weights can be an iterative learning process whereby the model is run, the user examines the results, adjust the weights and reruns. Bear in mind that the model is limited by what classes are available in the surrounding landscape so sometimes even radical adjustments to weights do not change model behavior much. Also consider that this is a relatively coarse approach and fine adjustments to weights is often times not warranted based on incomplete knowledge of the system and the imperfect nature of this model.

21. Use the “Lookup” tool to create a new cost raster with the values from the evt ‘WT’ column.
22. Run a “cost-distance” analysis using the park boundary as the ‘distance to’ layer and the cost raster you just created as the ‘cost raster’. There are many ways this can be done, one of which is by adding the spatial analysis toolbar, setting the extent and analysis mask to the evt layer in the options dialogue box and through the distance tools menu opening the cost distance dialogue. It is recommended that the user save the file to a location rather than to a temporary file. This processing step can take a very long time to run and/or crash ArcGIS depending on the size of the cost-raster and park so it is also recommend the the user guess at a maximum distance at which to stop the process. Something between 300 and 500 works for many instances although may not work for every park. If ArcGIS is crashing it is recommend that the user try to run the cost-distance step by itself with no other applications running and leave it overnight. Around 2 hours processing time is not uncommon for larger parks.

More details on cost-distance analysis:

Cost distance is a function of the weight you assign to cell values as well as distance as described by the following illustration and equation:

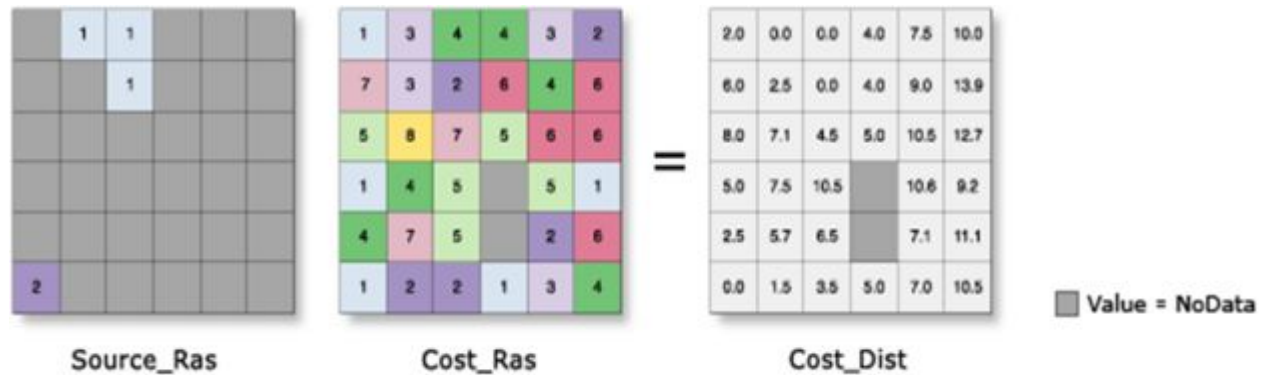


Figure 7. Cost-distance analysis example from ESRI.com

$$A1 = (cost1 + cost2)/2$$

$$A2 = (cost2 + cost3)/2$$

(for diagonals) $A3 = 1.414214(cost3 + cost4)/2$

$$accumulated\ cost = A1 + A2 + A3$$

The function attempts to calculate a least cost path from each source cell (each park). It is in this least cost step and the thresholding of a maximum cost-distance that cells with higher weights are excluded (they incur a greater cost to cross and hence a higher cost-distance).

In table 3 above weights are assigned to classes that are high, but not insurmountable by the cost-distance model. The user might notice that the contiguous habitat layer has expanded into developed or agricultural areas, but that the boundary is significantly attenuated in these areas. This is a result of the higher weights assigned to these areas. The user can experiment with these weights to see how they change model results.

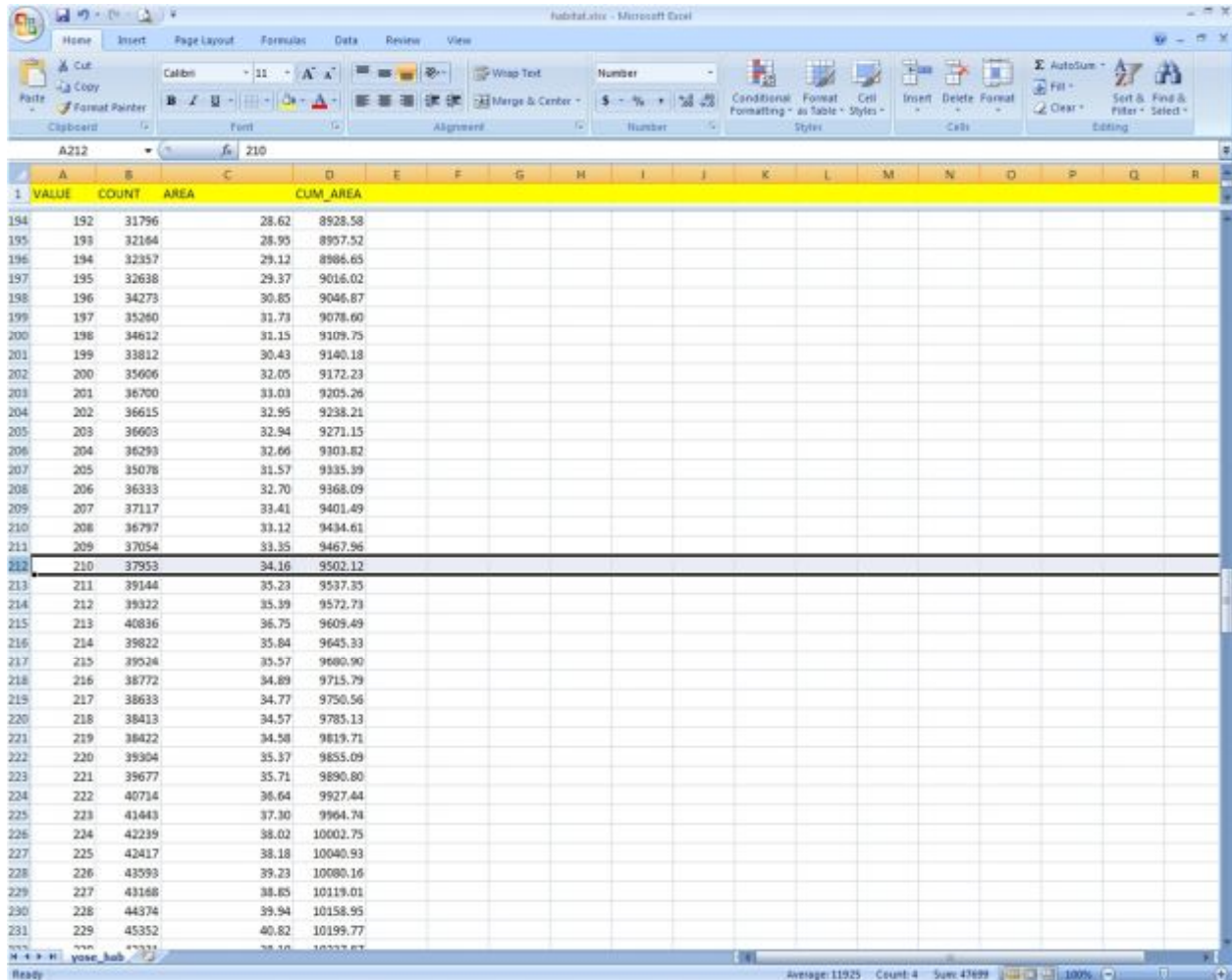
23. Using the "INT" command convert the cost distance raster to an integer raster.
24. Open the integer raster's attribute table and "add" a double field called 'AREA'.
25. Use the "Field Calculator" to make [AREA = COUNT*900/1000000], to convert to square kilometers.
26. "Export" this table as a .dbf and open in excel.
27. "Add" a field for cumulative area in which area will be accumulated from each cost-distance measure.
28. Make the first row of the new column equal to the area represented in the same 'AREA' column by typing the following in the equation box: [=C2].
29. Make the second row of your new column equal to the first row plus the second row of the 'AREA' column: [=C2+D3].
30. With D3 as the active cell, grab the lower right-hand portion of the cell with the cursor and drag it down the entire length of the cumulative area column to expand this equation and accumulate area across all cost distances in the sheet.
31. Using the target number that was calculated in the Species_area.xlsx file column ECO_AREA, row 67 based on park specific information, find the nearest and next higher number in the cumulative area column and to which 'VALUE' it is associated (depicted in

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the below graphic). For instance if the target area was 9484 square kilometers and there was an AREA 9467.96 and AREA 9502.12, the user would select the AREA 9502.12 which corresponds to VALUE 210 as shown below:

If the cumulative area values end before they've reached your target area you'll need to rerun the cost-distance tool with a higher maximum value, see step 18 this section.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	VALUE	COUNT	AREA	CUM_AREA														
194	192	31796	28.62	8928.58														
195	193	32184	28.95	8957.52														
196	194	32357	29.12	8986.65														
197	195	32638	29.37	9016.02														
198	196	34273	30.85	9046.87														
199	197	35280	31.73	9078.60														
200	198	34812	31.15	9109.75														
201	199	33812	30.43	9140.18														
202	200	35606	32.05	9172.23														
203	201	36700	33.03	9205.26														
204	202	36615	32.95	9238.21														
205	203	36603	32.94	9271.15														
206	204	36293	32.66	9303.82														
207	205	35078	31.57	9335.39														
208	206	36333	32.70	9368.09														
209	207	37117	33.41	9401.49														
210	208	36797	33.12	9434.61														
211	209	37054	33.35	9467.96														
212	210	37953	34.16	9502.12														
213	211	39144	35.23	9537.35														
214	212	39322	35.39	9572.73														
215	213	40836	36.75	9609.49														
216	214	39822	35.84	9645.33														
217	215	39524	35.57	9680.90														
218	216	38772	34.89	9715.79														
219	217	38633	34.77	9750.56														
220	218	38413	34.57	9785.13														
221	219	38422	34.58	9819.71														
222	220	39304	35.37	9855.09														
223	221	39677	35.71	9890.80														
224	222	40714	36.64	9927.44														
225	223	41443	37.30	9964.74														
226	224	42239	38.02	10002.75														
227	225	42417	38.18	10040.93														
228	226	43593	39.23	10080.16														
229	227	43168	38.85	10119.01														
230	228	44374	39.94	10158.95														
231	229	45352	40.82	10199.77														
232	230	45331	39.10	10238.87														

Figure 8. Identifying a threshold cost-distance

32. Go back to ArcGIS and open the "Reclassify" tool. Input the cost_distance_integer raster, with 'VALUE' as the reclass field and enter 0 – X (where X = the threshold VALUE you identified in the previous step), as the old values and '1' as the new value and everything else = 'NoData' as depicted in the image below:

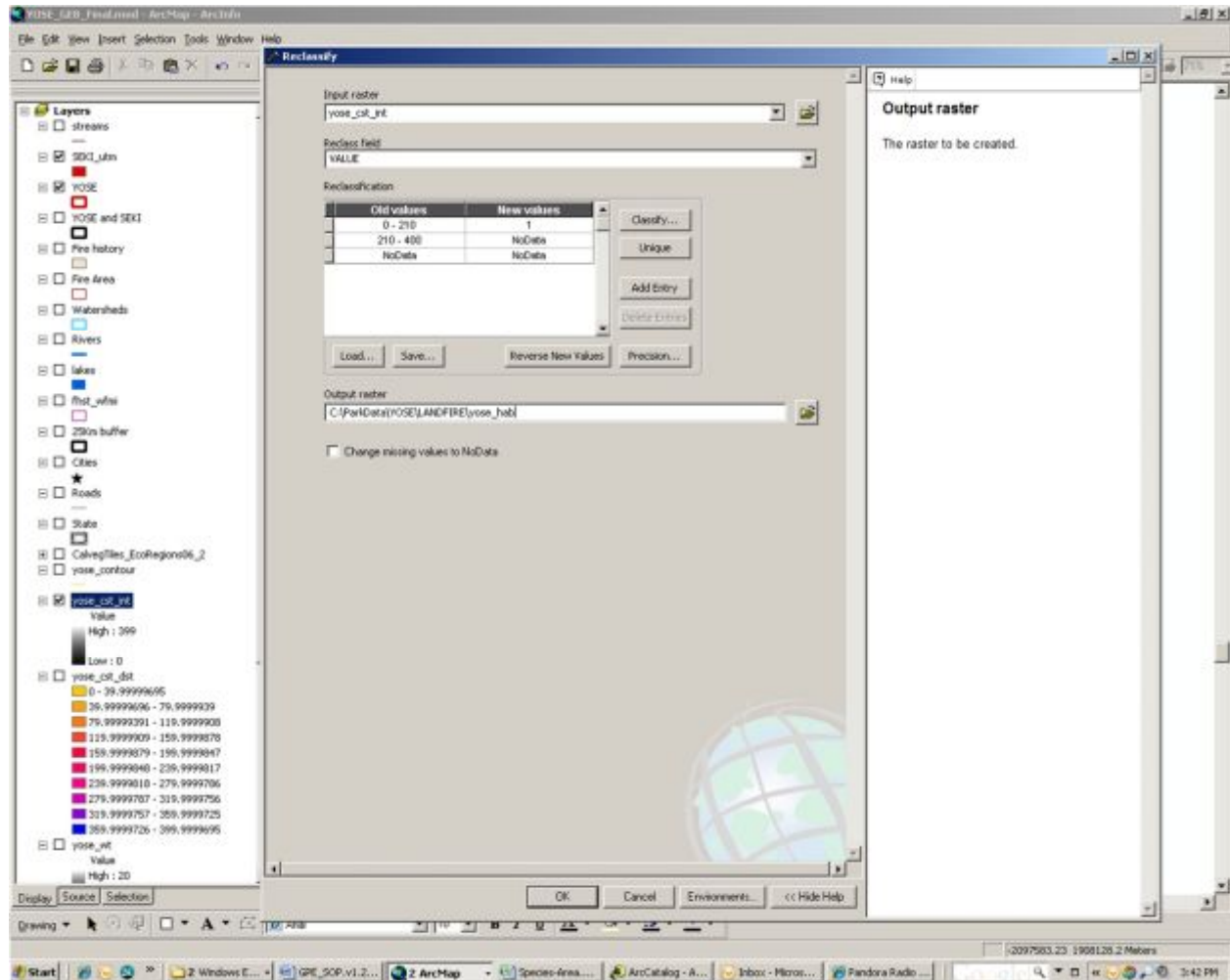


Figure 9. Thresholding your cost-distance layer to the contiguous habitat criteria target area

The resulting raster represents your contiguous habitat area.

33. If there are highly irregular edges or donut holes that the user would like to generalize (remember this is a coarse approach), it is recommended that you do so at this point using the raster “expand” and “shrink” commands and 30 - 50 cells if using 30M resolution raster data.
34. When the user is satisfied with the final area, use the “convert raster to polygon tool” (do not check the ‘simplify polygons’ box), to output a polygon layer that will be unioned with other criteria in a later step.
35. If this step was completed for 2 parks separately the user will need to “union” the results together to represent the contiguous habitat for both parks together. There may be overlap between the 2 areas which would be expected since there was reason to generate a PACE boundary for these 2 parks together. If the results are two

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discontinuous contiguous habitat areas, the user may want to reconsider creating a single PACE boundary for these 2 parks together.

Wrap-up

- If upon inspection the user finds that there are specific areas that the user wanted to have included in the PACE boundary that were not captured by this exercise, the user can either go back and adjust vegetation class weights or include these areas in the Crucial Habitat criterion.
- Inspect and get input from local experts

Edge effects of human activity

This step attempts to identify areas outside of the park where the effects of land use change and human activity may impact resources within the park. Whereas other criteria have estimated the dimensions of areas necessary to sustain park species and ecosystem function at present, this criteria ensures that a large enough area is included to protect species within the PACE from the detrimental effects of human activity adjacent to the park in the future. Detrimental effects can include super-abundance of non-natives or the effects of human pets on wildlife. There are hosts of example effects that this criteria is meant to capture. Although this criterion is “effects” based, it is ecological in its attempt to include all areas necessary to preserve species and ecosystem function. The buffer distance used in this step comes from maximum distances reported in the literature and expert opinion.

(See appendix A for specific literature cited).

Potential Issues

- ✓ There is limited knowledge and/or data in this arena so analysis is severely limited.
- ✓ Private lands within a 25 kilometer buffer are often discontinuous from other PACE criteria and the user must decide whether to retain these as disconnected areas or incorporate as contiguous areas to the park or other criteria.

Instructions

1. “Buffer” the park boundary by 25km.
2. “Add data” the included CUS_uppt_100 raster which is a national coverage of protection status. (The user may use any other layer of protection status).
3. Use the “extract by mask” tool to subset the CUS layer to the 25km park buffer.
4. “Reclass” the raster so that the private lands [VALUE = 1], remain 1 and everything else is reclassified as ‘NoData’ as shown in the following graphic:

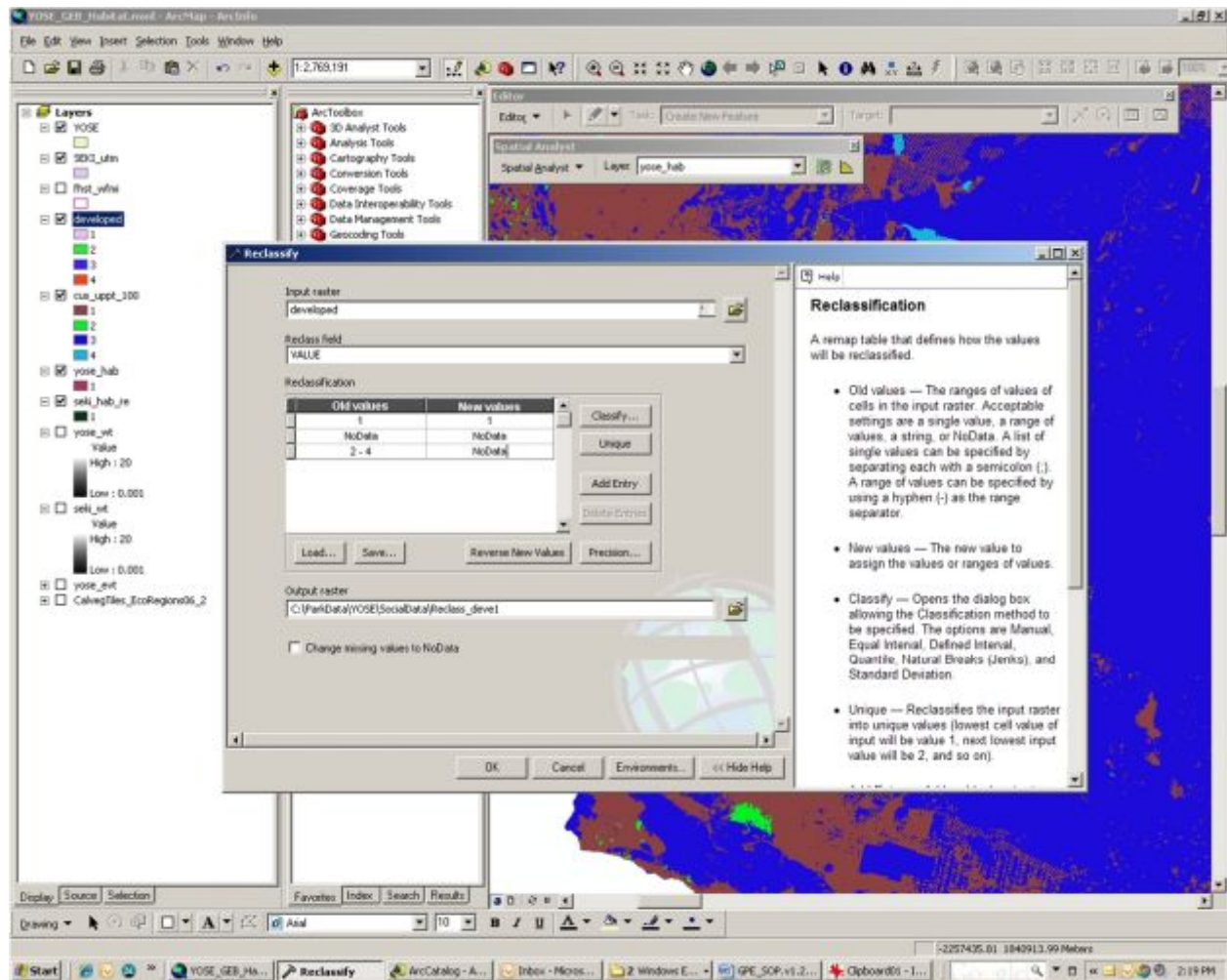


Figure 10. Reclassifying developable areas

5. Generalize using raster “expand” and “shrink” as necessary.
6. Incorporate discontinuous areas into the criteria’s final boundary as the user sees fit.

In our experience using the raster expand and shrink commands generalize these layers nicely and appropriately. Keep in mind that this raster layer is natively 100 meter resolution so the 30 – 50 cell rule of thumb used elsewhere in this document no longer applies. It’s equivalent for a 100M raster is 3 – 5 cells ($[100*100]X = 30*30*50 = 4.5$).

Wrap-up

- Expert and local knowledge can contribute important insight to this criterion.

Additional Criteria

The preceding criteria are only meant to represent a core set of criteria to apply to every park. There may be other criteria that would need to be incorporated at a given park in order to capture all outside park areas that have the potential to influence park species, resources and ecosystem processes. There is also a balance between delineating an area of reasonable scope with defensible ecological connections to park resources and one that encompasses the entire state, region, hemisphere, or world. Indeed, parks are but one small part of a vastly complex interconnected ecological world. The user will have to consider trade-offs in applying additional criteria. The methods detailed above provide logic and a model for the implementation of additional criteria.

Finalizing draft PACE boundaries

This step unions the results of all PACE criteria layers into one boundary. This simplifies disparate criterion boundaries into one ecosystem boundary for input to other tasks. Rather than a union of all criteria into one boundary, the user may consider other ways to represent a park-centered ecosystem boundary.

Potential Issues

- ✓ PACEs may be best represented as gradients of decreasing strength of interaction rather than hard and fast boundaries on the landscape. However, the approach outlined in this SOP document has created hard and fast boundaries as an entry-point to the topic, as a mapping exercise and as a way to identify candidate areas for appropriate outside park monitoring and research.

Instructions

1. “Union” the polygon outputs from the previous steps.
2. “Dissolve” these polygons into one feature.
3. If there continue to be highly irregular edges or donut holes that the user does not feel are justified, the user may further generalize by “converting this layer to a raster” and using “expand” and “shrink” or by “editing” the vertices of the polygon by hand.
4. “Export” generalized raster back to a polygon shapefile for input to other tasks.

Wrap-up

- As has been suggested in the Wrap-up section of each section, it is strongly recommend that this PACE layer is circulated to park staff and subject-matter experts before finalization and broader distribution. It’s likely that the user will go through several rounds of edits depending on how much input you’ve gotten from other sources up to this point.
- Vesting the PACE boundary with all stake-holders is another important step prior to finalization and implementation in other activities given potential political sensitivities.
- Steps to finalize a PACE boundary will vary on a case-by-case basis.
- Finally, a PACE boundary is not static. These methods may be repeated in the future as data, methods and ecological understanding of each park improves.

Evaluating PACE Boundaries

The final PACE boundary is a union of the results of all implemented criteria. As such, it's important to examine how each criterion has contributed to the total PACE area relative to others. As a mapping exercise that is necessarily subjective in some of its components, the evaluation of final results can give the user an idea of the extent to which subjective decisions implemented with each criterion's mapping has contributed to the final boundary. If the results of multiple criteria support the inclusion of certain areas in a final PACE boundary, then the user can conclude with greater confidence that this area should in fact be included in the boundary. If the boundaries of each criterion largely overlap then the mapping exercise has not relied as heavily on the subjective decisions made in the implementation of any single criterion. Jaccard's analysis of similarity provides a useful metric with which to perform this evaluation.

Potential Issues

- ✓ Interpretation of the jaccard's index can be confusing.
- ✓ The jaccard's index is sensitive to both overall criteria size, as well as extent of overlap with other criteria.
- ✓ Because the the methods used in the development of some criteria (i.e. watershed, contiguous habitat and disturbance), grow the criteria area from the park's boundary these will necessarily overlap in areas immediately adjacent to the park and therefore have somewhat inflated jaccard's values as compared to the crucial habitat and developed areas criterion which do not have to be contiguous with the park's boundaries.

Note that a compliment or alternative to jaccards is presented at the end of this section

The Jaccard's index of similarity equation is as follows, where:

JI = jaccard's index

A = intersection of criterion X and union of all other criteria

B = area of union of all other criteria that lies outside of criterion X

C = area of criterion X that is outside of the union of all other criteria

$$JI = A/(A+B+C)$$

Jaccard's values vary from 0 to 1, where:

1 = perfect overlap among all criterion

0 = no overlap among criterion

Conclusions of jaccard's analysis by each criterion:

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Near 1 = the area identified by this criterion largely overlaps with areas identified by other criteria so that the assumptions in implementing this criteria do not stand on their own, but rather are supported by the assumptions of other criteria.

Near 0 = the area identified by this criterion does not overlap with the areas identified by other criteria so that the assumptions in implementing this criteria stand on their own without the support of other criteria.

Note that a near '0' jaccards may also result from the criterion of interest being very small relative to other criteria and the PACE as a whole (i.e. if the criterion is small the numerator 'A' will also be small and 'B' in the denominator will be large).

Note also that criterion which through their methods of implementation builds outwards from the park's boundaries (e.g. watersheds and disturbance), will overlap with one another to a greater extent than criterion which can be discontinuous from the park's boundaries.

This is a index which requires some thoughtful interpretation by the user.

Conclusions of jaccard's analysis averages by PACE boundary:

Near 1 = there is considerable support for the complete final PACE boundary and the assumptions made in the implementation of each criterion.

Note that in our experience mean Jaccard's values for a park above 0.6 are "high".

Near 0 = the assumptions and subjective decisions made in the implementation of each criterion stand on their own as defensible or not.

In our experience mean Jaccard's values for a park below 0.3 has been "low".

Each criterion included in this mapping exercise is meant to be unique and it would not be surprising that they would each make unique contributions to the PACE boundary. However, as a park-centric exercise, each criterion builds from the park boundary outwards so there will be some baseline level of overlap among criteria. jaccard's values near 0 should not raise immediate concern. However, it does indicate that areas mapped by this individual criterion (or all criteria in the case of an average jaccard's value), are unique and stand on their own.

More about the jaccard's index and its more typical application to binary datasets can be found here:

http://en.wikipedia.org/wiki/Jaccard_index

Instructions

The following are instructions for how to use the attached aml (Arc macro language), file to calculate jaccard's index values for each criterion. The aml file is an example of a way to save time and key-strokes and requires that the user have ArcINFO workstation installed. The user

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can achieve the same results by running each step by itself in desktop ArcGIS. Those steps are not presented below, but can be deciphered from the Arc macro script.

1. Delivered along with this SOP is a file called "code_abcde.aml", open this in notepad and review its steps.

Text that follows `/****/` are comments documenting what is being done at each step

2. Use the "Erase" tool to delete areas of criteria shapefiles which overlap the park area so that this will not bias the jaccard's results.
3. Move the shapefiles from step #2 to a common workspace folder and either rename them "filenamea.shp, filenameb.shp...", OR modify the code_abcde.aml file so that each filename, b, c etc. is changed to actual file names. If the user chooses to rename the files, be sure to keep track of which criteria is associated with "filename, b, c" etc.
4. Open an Arc: prompt in ArcINFO workstation.
5. At the prompt change your workspace by typing:
`Arc: w c:/workspace`
5. Run the AML (arc macro language) file by typing the following:

`Arc: &run code_abcd.aml`

6. ArcINFO will work through each step in the aml file and finish by outputting a table with 'VALUES' and 'COUNTS'.

If ArcINFO returns the error message:

File not found

AML MESSAGE – Stopping execution of AML file due to ERROR condition

Look further up in the output for a message stating that "all cells in one of the grids have NODATA value and VAT will not be built". This usually occurs when one of the criteria does not contribute any area unique to the union of all other criteria. This is not uncommon. The user will have to record the results output to that point including a '0' for the file with NODATA values, open the 'code_abcde.aml' file and delete the "list" command at the very bottom that references the file that only contained NODATA values and rerun to obtain the remaining values. Before rerunning the user will have to either establish a new workspace in which to run the .aml, or delete all prior outputs stored in the current workspace as ArcINFO will not overwrite files of the same name.

7. Open the attached MS Excel file named "jaccards_results_sheet.xls".
8. VALUE 1 in the ArcINFO output table refers to calculation A for the first input shapfile, enter this number in the spreadsheet. VALUE 11 refers to calculation A for the second input shapefile, VALUE 111 to calculation A for the third input shapefile, VALUE 2 to calculation B for first input file etc.

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9. Enter the numbers from the ArcINFO output table into the excel spreadsheet and the values in the 'SUM' and 'jaccards Index' columns should update to reflect the calculated jaccards index values for each criterion and the mean value for this park as depicted in the graphic below.

The Arc and GRID command 'quit' exits these functions of ArcINFO workstation and closes the Arc command prompt and window.

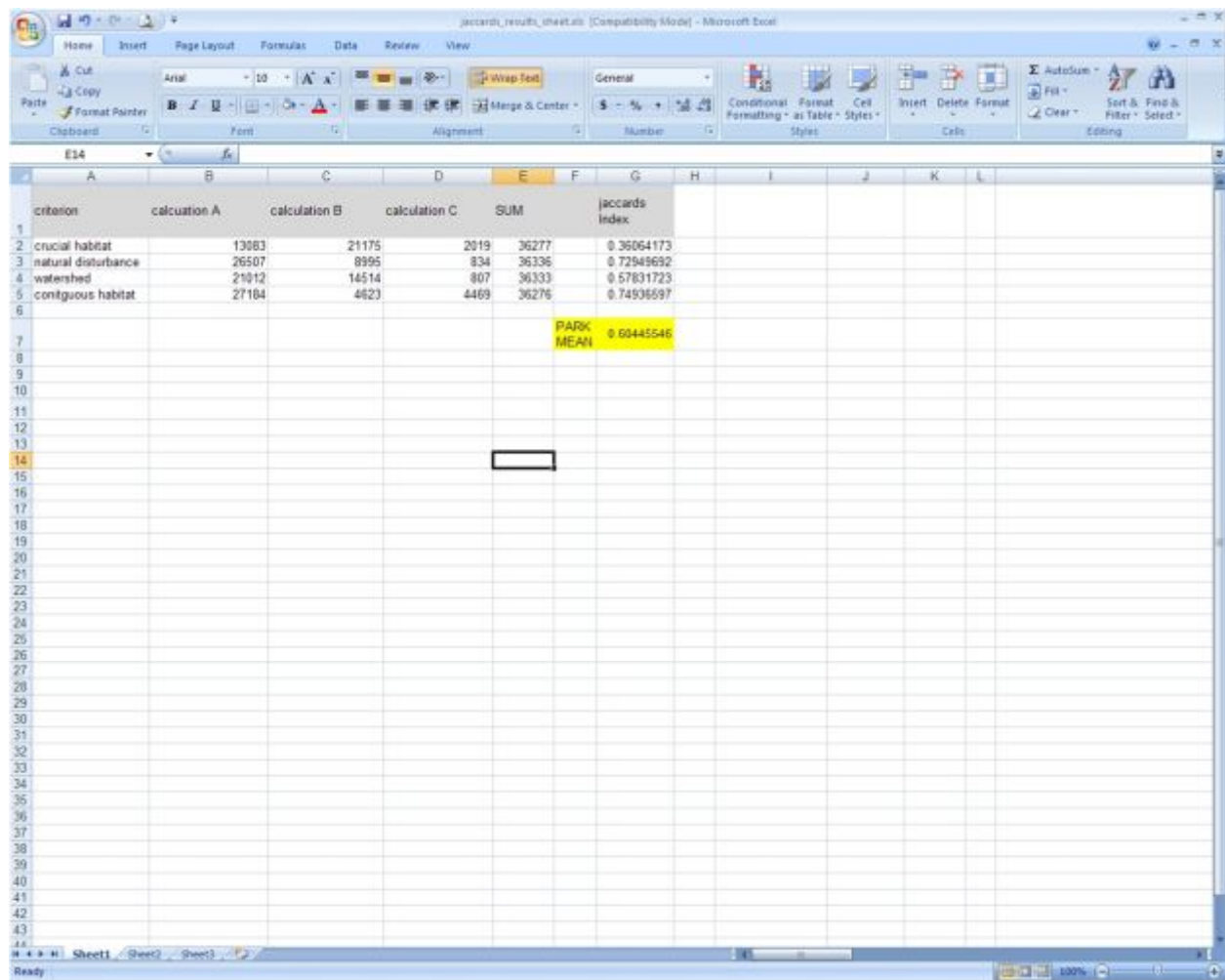


Figure 11. Calculating the jaccard's index of similarity for each PACE criterion

An alternative to jaccards:

Because the jaccard's index can be difficult to interpret, those users who wish to evaluate the relative contributions of each criteria with more simple methods can perform the following

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analysis which present the percentage that each criteria uniquely contributes to the final PACE area.

Instructions

1. Create a new column in the "jaccards_results_sheet.xls" spreadsheet for percent of total area which is uniquely contributed by each criteria.
2. The 'SUM' column represents the total final PACE area and 'calculation C' the area where the criteria of interest alone is present. Divide calculation C by the SUM and input those numbers to the new column.

The user can interpret that criteria that uniquely represent a high percentage of a PACE final boundary is most influencing the PACE estimation process. As such, the assumptions inherent in the application of that criteria stand alone and the areas mapped by that criteria are only as defensible as the mapping procedure for that criteria.

Wrap-up

- Evaluate the relative contributions of each criterion to the park's final PACE boundary.
- Consider the assumptions and subjective decisions made in the implementation of each criterion and these methods.
- Consult local subject-matter experts where there remains doubt about the inclusion (or exclusion), of any specific areas in the PACE boundary.

Literature cited

See appendix A and the literature referenced in the draft manuscript presented therein on pages 47 – 85 of this document.

Appendix A . A Bioscience manuscript

Title: Delineating the Ecosystems Containing Protected Areas for Monitoring and Management

Authors: Andrew Hansen¹, Cory Davis², Nathan Piekielek³, John Gross⁴, Dave Theobald⁵, Scott Goetz⁶, Forrest Melton^{7,8}, Ruth DeFries⁹

¹Professor, Ecology Department, Montana State University, Bozeman, MT, 59717, USA (hansen@montana.edu). ²Research Assistant, Ecology Department, Montana State University, Bozeman, MT, 59717, USA. (cory.davis@msu.montana.edu), ³Research Assistant, Ecology Department, Montana State University, Bozeman, MT, 59717, USA. (npiekielek@gmail.com), ⁴Ecologist, National Park Service, Inventory and Monitoring Program, 1201 Oakridge Drive, Suite 150, Ft. Collins, CO 80525, USA. (John_Gross@nps.gov). ⁵Research Scientist, Natural Resource Ecology Laboratory and Natural Resource and Department of Human Dimensions of Natural Resources, Colorado State University, Fort Collins, CO, 80523, USA. (dave@cnr.colostate.edu), ⁶Senior Scientist, The Woods Hole Research Center, 149 Woods Hole Road, Falmouth, MA 02540, USA (sgoetz@whrc.org), ⁷Senior Research Scientist, Division of Science and Environmental Policy, California State University Monterey Bay, 100 Campus Center, Seaside, CA 93955, USA. (forest@gaia.arc.nasa). ⁸ NASA Ames Research Center, Moffett Field, California 94035, USA. ⁹Denning Professor of Sustainable Development and Professor, Ecology, Evolution, and Environmental Biology, Columbia University, New York, NY, 10027, USA. (rd2402@columbia.edu).

Abstract. Park managers realized more than 130 years ago that protected areas are often subsets of larger ecosystems and are vulnerable to change in the unprotected portion of the ecosystem. We illustrate the need for delineating “protected-area centered ecosystems” (PACES) by using comprehensive scientific methods to map and analyze land-use change within PACES around 13 US National Park units. The resulting PACES were on average 6.7 times larger than the parks for those in upper watersheds and 44.6 times larger for those in mid watersheds. The sizes of these PACES clearly emphasized the long-term reliance of park biodiversity on surrounding landscapes. PACES in the eastern US were dominated by private lands with high rates of land development, suggesting that they offer the greatest challenge for management. Delineating PACES more broadly will facilitate monitoring, condition assessment, and conservation of the large number of protected areas worldwide that are being degraded by human activities in the surrounding areas.

Keywords: protected area, ecosystem, land-use change, monitoring, management

The global portfolio of protected areas has been expanded dramatically in recent decades (Naughton-Treves et al. 2005). During this period, however, it is increasingly evident that many established protected areas have undergone degradation (Gaston et al. 2008). Ecological processes such as disturbance regimes have been altered within protected areas, exotic species have expanded, and native species have gone extinct (Stohlgren 1998, Pringle 2001, Parks and Harcourt 2002). Recent assessments have found that most terrestrial reserves are adequately protected within their borders (Bruner et al. 2001). The predominant force causing degradation within protected areas is likely increasing human population density and land use intensification on the surrounding lands (Brashares et al. 2001, DeFries et al. 2005, Wittemyer et al. 2008). The current challenge is to maintain the ecological condition of protected areas, given changes on the lands surrounding them (DeFries et al. 2007).

The potential for degradation of protected areas has long been anticipated by scientists who observed that protected areas are often subsets of larger ecosystems (Shelford 1933, Wright and Thompson 1935). Flows of energy, materials, and organisms often occur over an expanse larger than the protected area and link the protected area to a larger surrounding ecosystem (Hansen and DeFries 2007). Human activities on surrounding lands may either disrupt natural flows between the protected area and the surrounding ecosystem or create new harmful flows, such as of exotic species. These alterations of flows may disrupt ecological function and the viability of native species within protected areas.

The need to identify the larger ecosystems around protected areas was realized just a decade after creation of the world’s first National Park when the US Congress in 1882 considered legislation to expand Yellowstone National Park’s boundaries to accommodate migratory ungulates (Haines 1977). Subsequently, movements of wildebeest were used to delineate the Serengeti National Park (Pearsall 1957) and home ranges of grizzly bears were used to define the Greater Yellowstone Ecosystem (Craighead 1979). The boundaries of the Greater Everglades Ecosystem were based on hydrological processes (Davis and Ogden 1994). In the 1970s, the Man in the Biosphere Program advocated the creation of buffer zones around protected areas to reduce negative outside influences (UNESCO 1974). More recently, guidelines were offered for mapping and managing the ecosystems around protected areas (Theberge 1989, Grumbine 1994, DeFries et al. 2010a, 2010b). The US National Park Service (USNPS) advocated establishing buffer zones around parks for much of its history (Shafer

1999). This position became politically untenable, however, in the 1980s when private land rights emerged as a national issue.

Interest in connections among national parks and surrounding lands has increased in recent decades due to several factors. Changing patterns of fire, insect outbreaks, flooding, and wildlife disease have lead many resource professionals to embrace management at larger spatial scales that involve multiple ownerships (Johnson et al. 1999). People living near national parks have increasingly recognized the socioeconomic benefits of the parks and support incentive-based conservation on private lands to keep parks healthy (Theobald et al. 2005, DeFries 2010a). The USNPS initiated an Inventory and Monitoring Program (Fancy et al. 2009) to assess conditions and trends in and around parks. Each of these interests desire a better understanding of the spatial domain of connections between parks and surrounding lands in order to prioritize the location of monitoring, research, and management.

In addition to increased awareness of connections between national parks and surrounding, managers of national parks and protected areas are increasingly concerned about the potential for the dual impacts of climate and land use change to both affect ecological processes within a park and to degrade the ecologically significant areas surrounding the park. This presents a practical need for resource managers to design monitoring programs to include parameters that can capture changes in areas surrounding parks and protected areas. Beyond park boundaries, however, designating the appropriate region for monitoring is a difficult challenge, and no detailed published methodology is available to assist park managers in defining geographic boundaries for monitoring of surrounding ecosystems. At an operational level, the simple problem of selecting the area over which to calculate summary metrics outside of the park boundaries can stymie the development of monitoring programs that would provide useful information to park managers on ecologically significant changes occurring beyond park boundaries.

The goal of this study is to build on previous efforts and illustrate a comprehensive scientific methodology for delineating the boundaries of the ecosystems encompassing individual protected areas. In particular, we sought to identify the zone around each protected area wherein human activities may influence important ecological processes and viability of populations of native organisms within the protected area. This area becomes the logical place to focus monitoring, research, and collaborative management needed in order to maintain protected area function and condition. We refer to these as “protected area centered ecosystems” or PACEs (see Box 1). In this paper we present a conceptual framework for delineating PACEs. We then apply the framework to map PACEs around 13 US National Parks, National Recreation Areas, or Scenic Rivers (hereafter termed park units). We then quantify land allocation and use in the PACEs to characterize the challenge of maintaining their ecological condition. Finally, we discuss the challenges and potential for integrating the PACE approach into protected area management more broadly across the US and globally.

A framework for mapping PACEs

We sought to develop a scientifically sound and repeatable method using objective ecological criteria and commonly available data sets to map PACEs. In order to make the results as relevant as possible to local resource managers, we incorporated local knowledge into the process. Our resulting framework (Fig 1) derives polygons around protected areas based on individual ecological criteria and then merges these layers to delineate PACE boundaries. Widely available regional and national data sets are used for most criteria. These are supplemented with local data where available (e.g. for local fire regimes). Each individual layer

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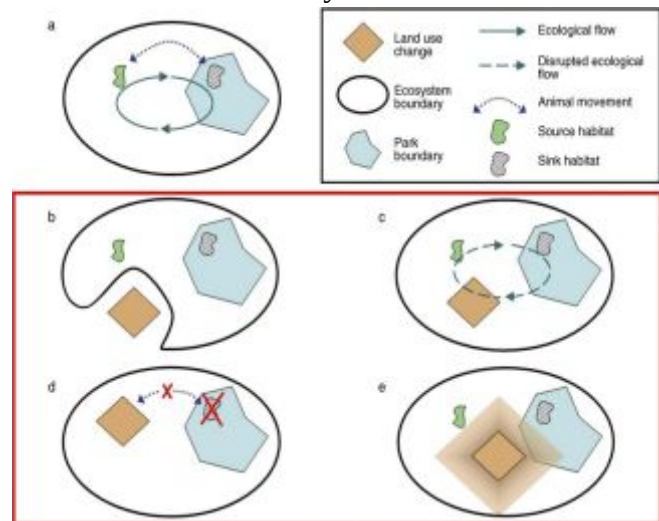
is reviewed by local experts and the mapping products are refined to best reflect local conditions. Various methods can be used to join the individual layers to form the PACE depending on local conditions and preferences. These include: taking the union of the individual polygons; weighting the importance of locations within the union based on number of criteria represented; and deriving the boundaries for the individual criterion using assumptions that bracket uncertainty in key parameters and representing this uncertainty with “fuzzy” PACE boundaries. We choose the second approach to help managers prioritize the importance of locations within the PACE based on the number of overlapping criteria.

The ecological criteria used as the basis for the PACE mapping were derived from the mechanisms described in Hansen and DeFries (2007). These mechanisms are thought to be the primary means by which land use in surrounding lands influences ecological processes and the viability of native species within protected areas. The mechanisms involve ecological flows, crucial habitats, effective size, and human edge effects in and around the protected areas and are illustrated in Box 1. The general methods used to map PACEs based on these mechanisms are described below.

Box 1: The concept of protected area centered ecosystems.

Many protected areas were designated based on factors other than ecological completeness, such as scenic value. Thus, they may not include the area that is needed to maintain essential ecological processes and organisms within them. In panel a in the figure, the protected area is strongly connected to a larger surrounding area by the flows of energy, materials, and/or organisms. Land use change in the unprotected part of the ecosystem may disrupt ecological function and biodiversity within the protected area through any of four primary mechanisms.

1. *Effective size*: Human activities may destroy natural habitats and reduce the effective size of the larger ecosystem which can: simplify the trophic structure as species with large home ranges are extirpated; cause the size of the ecosystem to fall below that needed to maintain natural disturbance regimes; and reduce species richness due to the loss of habitat area (b in the figure).
2. *Ecological flows*: Land use may alter characteristics of the atmosphere (climate, pollution), water (quantity, quality, nutrients, water-borne organisms), and natural disturbance (frequency, size, intensity) moving through the protected area (c in the figure).
3. *Crucial habitats*: Land use may eliminate or isolate crucial habitats, such as seasonal habitats, migration habitats,



Conceptual model illustrating the ecosystem containing a protected area (a) and the mechanisms by which land use change can alter biodiversity within the protected area (b-e).

- or habitats that support source populations (d in the figure).
4. *Edge effects*: Land use may increase human activity along park borders and result in the introduction of invasive species, increased hunting and poaching, and higher incidence of wildlife disturbance (e in the figure).

In this paper, we use these four mechanisms as a basis for objectively mapping the spatial extent of the ecosystems containing national parks. Mapping these “protected-area centered ecosystems” provides guidance to resource managers on where to concentrate monitoring, research, and collaborative management to maintain the health of the protected area.

Source: Hansen and DeFries 2007.

Details of the methods can be found in Appendix 1 and ARG-GIS commands for executing the mapping are in Piekielek et al. (2010).

Ecological flows include those that are water borne or airborne and movements of disturbances such as fire. Water, sediment, nutrients, and organisms move with water flows through watersheds. Land use in upper watersheds may alter these flows into protected area.

Similarly, land use upwind in airsheds may change climate or pollution levels downwind in protected areas. Disturbances (e.g. fire) may originate outside and move through a protected area. The condition of the disturbance initiation zone influences the likelihood of disturbance moving into the protected area. Runout zones, defined as the places where disturbances terminate (such as debris flow deposition areas), may provide unique habitats for some species (Baker 1992). We mapped watersheds connected to the protected areas using the hydrological units delineated in the Watershed Boundary Dataset developed by the US Natural Resource Conservation Service (<http://datagateway.nrcs.usda.gov>) [Accessed 01/10/2009]. Unlike watersheds, national maps of airsheds are not currently available. While regional data sets would allow airshed delineation for some national parks, such data were not available for the parks included in this study and the airshed criteria was not included in the mapping. For the disturbance criterion, we used historic data sets to map the boundaries of potential disturbance initiation and runout zones for protected areas which experience contagious disturbances (e.g., fire, flooding, insect infestations).

Seasonal habitats, population source areas, movement paths, or portions of large home ranges for populations within protected areas may lie outside the protected areas. Land use may alter or destroy these crucial habitats. The PACE should be of sufficient size such that self-sustaining populations of species with habitat requirements not met within the protected area can be maintained within the PACE. Typically, species-specific quantitative data are available only locally or for a limited number of species. For the crucial habitat criterion, we drew on such data and local expert opinion to identify and map crucial habitats outside of the protected areas that are required by populations within protected areas during important seasonal or life-history stages.

The habitat requirements and movements of many organisms are not known adequately to quantify their crucial habitats surrounding a protected area. We used a “coarse filter” approach (Noss and Cooperrider 1994) to deal with these lesser-known species based on species-area relationships. The number of species within a protected area is influenced by its size and by its connectivity to adjacent habitats. An “isolated” protected area is expected to have fewer species than one embedded in a larger area of contiguous habitat (Cowlinshaw 1999). For the effective size criterion, we determined the area of contiguous habitats surrounding a protected area required to prevent the loss of species from the protected area due to isolation by destruction of surrounding habitats using the methods of Brooks et al. (1999).

Human presence on the periphery of protected areas may cause changes in ecosystem processes and biodiversity that extend varying distances into the protected area (e.g., hunting, poaching, outdoor recreation, pet effects on wildlife, exotic species). The extent to which human activities outside a protected area may penetrate into adjacent protected areas varies with activity and social and biophysical setting. For the edge effects criterion, we used a buffer of 25 km around the protected area, which was selected to exceed known edge penetration distances from the literature. Within this area all private, non-protected land was selected. Additionally, we included a 5-km buffer around private lands that lay outside the 25-km buffer but adjacent to polygons selected by the crucial habitat criteria above. Edge effects from land use intensification in this 5-km buffer could degrade crucial habitats and ecological processes that are more distant from the protected area, hence they are also included in the PACE boundaries.

Applying the framework. We applied the methods to 13 US park units administered by the USNPS (Table 1). We selected parks only in the contiguous US to increase consistency of biophysical datasets. Our goal was to include a representative subset of USNPS units to

demonstrate proof of concept and lay the foundation for application of the approach to additional USNPS units and other protected areas. Criteria for selection were: wide geographic, ecoregional, and physiognomic distribution; diverse land allocation types in surrounding areas; variation in park size and shape; and concentration within relatively few USNPS Inventory and Monitoring (I&M) networks to facilitate coordination with USNPS personnel. The watershed, contiguous habitat, and human edge effect criteria were applied to all of the park units. The disturbance criterion was applied to North Cascades National Park Complex, Yosemite and Sequoia-Kings Canyon National Parks, and Yellowstone and Grand Teton National Parks where fire is an important disturbance and the required data were available. The species for which crucial habitats were considered varied by park unit and were largely identified during the expert review phase. An initial PACE map was made using national datasets for the watershed, contiguous habitat, and human edge effect criteria. Consultation with local USNPS I&M staff and park scientists was used to evaluate the airshed, disturbance, and crucial habitat criteria. The final maps were developed through two cycles of sending initial maps and description of methods to local NPS scientists and modifying based on their comments and spatial datasets they provided.

The resulting PACE boundaries are depicted in Figure 2 and their spatial characteristics are presented in Table 2. The sizes and shapes of the mapped PACEs varied among the study units. The PACEs of parks in close proximity merged into single ecosystems. This was the case for: Yosemite and Sequoia-Kings Canyon National Parks; Yellowstone and Grand Teton National Parks, Bighorn Canyon National Recreation Area; and Delaware Watergap National Recreation Area and Upper Delaware Scenic and Recreational River. The portion of the PACEs outside of the park units were on average 6.7 times larger than the park units for those situated in the upper portions of watersheds. These PACEs were centered on the park units and their shapes tended to be similar to those of the park units. For park units situated in mid-watersheds (Big Horn Canyon National Recreation Area, Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River) this value was 44.6 times the area of the park unit. Their shapes reflected the nature of the upper and/or lower portion of the watersheds within which they lay.

Park managers were interested in the extent to which the final PACE boundaries were due to a single criterion versus two or more criteria. Thus, in Figure 2 gradations in color are used to indicate the number of overlapping classification criteria in the PACE. Places with many overlapping criterion may be considered more important for monitoring and management. Yellowstone and Grand Teton National Parks, Olympic National Park, and Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River showed relatively high levels of overlap in criteria (67-78% with two or more criteria). In contrast, the watershed criteria uniquely covered 73% of the Big Horn Canyon National Recreation Area PACE and the contiguous habitat criterion uniquely covered 65% of the Rocky Mountain National Park PACE. Hence, managers of Big Horn Canyon National Recreation Area and Rocky Mountain National Park may wish to carefully scrutinize the use of these criteria for delineating final PACE boundaries.

Evaluation of land allocation and use within PACEs. We evaluated the characteristics of PACEs that may influence the challenge of maintaining ecological condition within national parks. These characteristics included:

- Ownership – proportion of PACE area in public versus private ownership
- Proportion developed – percentage of the private lands in agriculture, near roads, or with home densities that exceeded a minimum threshold

- Home density – total number of homes in 2000 (most recent census)
- Change in home density – percentage change in home density from 1940 to 2000

Ownership classes were primarily derived from the Protected Area Database v4.6 (IUCN 2003) with some additional datasets to provide more recent data on protected lands. Percent of private lands that were developed in 2000 were defined as the sum of areas of roads (US Census Bureau 2009), croplands (USGS 2005), and areas with home densities of greater than 0.031 units per hectare all divided by the total area of private land. Areas with home densities below this threshold were assumed to be little influenced by land use (Theobald 2005). The home density data were from Theobald (2005) and Bierwagen et al. (in press) who down-scaled home density estimates from US Census blocks to a 1 ha resolution based on groundwater well density, accessibility to urban areas along roads, land-cover characteristics, and other factors for the period 1940-2000. Roads layers were used to identify developed areas by including buffers of 5 to 15 m based on their level of use and following the work of Forman (2000).

The PACEs lay along gradients in ownership and land use. Big Horn Canyon National Recreation Area was unique in being relatively low in percent private land and very low in percent of private land developed, home density, and home density growth rate since 1940 (Figure 3). At the other extreme, the three eastern-most PACEs were high in percent private land and in the percent of this private land developed. Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River and Great Smoky Mountains National Park were also high in home density and Great Smoky Mountains National Park and Big South Fork National River and Recreation Area were high in growth rate of homes. The remaining PACEs were intermediate with regards to these axes. Thus, the evaluation of the PACEs revealed that the parks differ substantially in land use in their surroundings. Big Horn Canyon National Recreation Area, and to a slightly lesser extent Yellowstone and Grand Teton National Parks and North Cascades National Park Complex were unique in being embedded in a large semi-wild landscape of mostly public lands, with relatively little development on private lands. At the other extreme were Great Smoky Mountains National Park, Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River, and Big South Fork National River and Recreation Area which were surrounded mostly by private land, much of which is in exurban, suburban, and urban land uses. It is noteworthy that growth in home density since 1940 was higher in Great Smoky Mountains National Park and Big South Fork National River and Recreation Area than other parks, suggesting that these park units have been losing natural habitat in their PACEs over past decades faster than other park units. These findings on the characteristics of the PACEs suggest that maintaining ecological condition will be least challenging in Big Horn Canyon National Recreation Area, Yellowstone and Grand Teton National Parks, and North Cascades National Park Complex, intermediate in Yosemite and Sequoia-Kings Canyon National Parks, Rocky Mountain National Park, Mount Rainier National Park, Olympic National Park, and greatest in Big South Fork National River and Recreation Area, Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River, and Great Smoky Mountains National Park.

Coping with the challenges of defining PACEs

We believe this is the first attempt to develop and apply an objective framework for delineating ecosystems surrounding USNPS units. While the concept of PACEs has been long recognized, several theoretical and logistical issues make their delineation challenging. First, the spatial domains of ecological processes and organisms often do not have discrete boundaries (Theberge 1989). Rather, strength of interaction decreases as a function of distance and/or other factors. Objective rules for specifying the strength of interaction sufficient to be included in

the PACE are difficult to derive. Secondly, components of an ecosystem often differ in their spatial domains (e.g., hydrologic flows may not correspond with movements of migratory species). Thus, separate boundaries could be defined for each ecosystem component of interest. Thirdly, the spatial domains of some ecosystem processes may be orders of magnitude larger than others. Air pollution, climate, and long-distance migrations of organisms are examples of factors that may be expressed at continental and/or global scales. Lastly, knowledge is often lacking about the spatial domains of key ecological components in particular protected areas.

Our PACE framework builds on earlier studies (Craighead 1979, Theberge 1989, Davis and Ogden 1994, DeFries et al. 2010a,b) to overcome both theoretical and logistical challenges. We derived the criteria for mapping based on sound ecological theory (Hansen and DeFries 2007). We defined thresholds in strength of interaction based on objective criteria where possible (e.g., watershed boundaries), and based on local knowledge where key data were lacking (e.g., crucial habitats). We suggest that sensitivity analyses be used to map “fuzzy” boundaries for individual criterion when uncertainty in level of strength of interaction is considered an issue. We emphasized regional rather than continental scale interactions in deriving PACE boundaries because protected area managers often operate at regional scales. Our framework recognizes that different methods may be used to join the maps of individual criteria to define the PACE. A simple union of the individual maps provides a tangible boundary, which may help communicate the PACE concept to nonscientists. An alternative is to weight the PACE map based on the number of criterion that overlap. Places with high weight (many overlapping criterion) may be considered more important for monitoring and management. Finally, our framework also recognizes that knowledge and quantitative data will often be lacking for some criteria. Hence, we integrate review by experts with local knowledge into the process in order to take advantage of best current knowledge. We recommend that the process be repeated periodically to adjust for changing conditions and improved knowledge at intervals relevant to the particular protected area. The location and areas of the PACE can be an indicator of landscape change, and contribute to making fundamental linkages between the patterns of land use change and ecological processes.

Implications for conservation and management

The primary contribution of this work is to use the long recognized concept of protected areas as parts of larger ecosystems as a basis for mapping, analyzing, and managing this larger ecosystem. We have attempted to develop a credible, repeatable, science-based framework for delineating PACEs. The application to a collection of US National Parks demonstrated how ecological theory, widely available data sets, GIS software, and local expertise can be integrated to map the boundaries of such ecosystems. Rather than be considered as final PACE boundaries, we offer the results of this mapping effort as examples that can be refined by the NPS and/or other entities. The application also provides guidance on ways to modify and improve the framework as our knowledge and data improve.

Identifying PACEs may assist in management of protected areas in several ways.

(1) It should help managers, scientists, and local citizens better understand the connections between protected areas and surrounding lands. Such connections can be difficult to perceive, especially in the absence of remotely sensed data, animal movement data, and other evidence of such connections. Recognition of these connections is requisite to further action to maintain ecological condition of the protected area in the face of change in the surrounding ecosystem.

(2) Delineating PACEs helps identify locations critical for monitoring. Monitoring of biophysical factors, organisms, and human land use, demographics, and socioeconomics provides a context for understanding changes in PACEs and can provide early warning of impending threats to the protected area (Jones et al. 2009). The NPS I&M program has developed, and is implementing, such monitoring (Fancy et al. 2009). A key question NPS I&M scientists face is how large an area around parks should be included in the monitoring program. The PACE is a logical choice for the area to be monitored as this represents the area where there are strong connections between the protected area and surrounding landscape.

(3) Related to monitoring, the PACE can be used as the spatial unit for reporting of summary indicators such as rates of habitat loss, land use intensification, disturbance events, the total area affected by invasive species, and other factors as recommended by the NPS I&M (Fancy et al. 2009) and the Heinz Center (2003). These summary indicators can be compared between protected areas and the surrounding PACEs and between protected areas across the country. The outcome of such comparisons can be used to identify which places within a PACE or which PACEs in a network are undergoing the most rapid negative change and are highest priorities for research and management.

(4) Delineating the PACE should stimulate research on cross boundary interactions. Potential gaps in knowledge that arise during delineation may become high priority topics for research by protected area staff, improving understanding of interactions between the protected area and the surrounding PACE.

(5) Perhaps most importantly, identifying the PACE should help focus conservation actions aimed at maintaining ecological condition within protected areas. In cases where protected areas were established in the centers of large wildernesses, the PACE approach gives guidance on how to manage future human activities in the surroundings to maintain the protected area. More typically, the PACE includes considerable private lands and/or more intense human land uses. In this case, keeping protected areas functioning likely requires both managing within the protected area boundary to buffer outside influences and managing surrounding lands to minimize negative influences. Examples of potential management strategies in the PACE include conservation easements on important private lands, land-use planning to better optimize ecological and socioeconomic goals, and education programs for local landowners to help them minimize negative effects on ecosystems (Theobald et al. 2005).

(6) Finally, the PACE framework could be used in the establishment of new protected areas to help ensure that their boundaries include essential components of the ecosystem.

While the PACE framework is based on the effect of land use on protected areas, it is widely recognized that climate change is substantially influencing many protected areas (NPCA 2009). A next step for the PACE framework could be to develop objective criteria to identify areas around protected areas that are vital for adaptation of protected-area organisms to changing climate or for movement between protected areas to adjust to changing conditions. If not already included in the PACE, these areas could then be incorporated and monitored. Such approaches may be especially relevant to the emerging US Department of Interior Landscape Conservation Cooperatives (U.S. Fish & Wildlife Service 2009).

An important practical consideration with regards to the PACE approach is the potential influence on local residents and stakeholders. Delineation of PACEs may generate considerable concern or interest among local residents and other stakeholders. Around some US national parks, the history of lands taking by the federal government and other factors, have created considerable concern over retaining private property rights. Schafer (1999) chronicled how over a century of effort by the US National Park Service and others to expand US National

Parks and/or create buffers around them was largely halted in the 1980s by private land rights issues. Since that time, the NPS has put considerable effort into strengthening trust with neighbors. Our NPS collaborators have emphasized that delineation of PACE boundaries should be done in consultation with local stakeholders in order to maintain that trust.

In the U.S. since the 1980s, regulatory approaches have largely been replaced by incentive-based approaches to achieve conservation objectives. Many citizens increasingly recognize substantial benefit by living near healthy ecosystems (Power 2008). Ecosystem goods and services involving food, water, nature-based livelihood, and aesthetics are thought to partially explain why a disproportionate number of people live near protected areas globally (Rasker and Hansen 1990, DeFries et al. 2007, Wittemyer et al. 2008) and development is disproportionately high near US protected areas (Radeloff et al. 2010, Wade and Theobald 2010). Local people that value the ecological goods and services from protected areas may have high incentives to support collaborative management strategies in the PACE to maintain ecological condition within the protected area. Evidence of this is the vast acreage of private land that has been protected under conservation easements through the efforts of citizen supported non-governmental organizations, public open-space initiatives, and conservation land buyers (Theobald et al. 2005). The identification, monitoring, and evaluation of PACEs can be used to guide incentive-based conservation efforts to the most important lands for maintaining protected area condition.

While we have defined PACEs based on potential land use effects on ecological condition of protected areas, DeFries et al. (2010a,b) also mapped the zone of influence of protected areas on surrounding human communities. Such an approach recognizes protected areas and the surrounding human communities as a “coupled natural human system” (Liu et al. 2007) with strong interactions and feedbacks between the human and ecological components of the system. This later approach is more difficult to map objectively and communicate to stakeholders. However, it may ultimately better allow local people to understand the socioeconomic benefits of protected area conservation.

We hope that this work stimulates application of the PACE approach within the US and internationally. The USNPS is well equipped to apply the framework. Reception of the PACE conceptual approach and results by NPS personnel has been very positive. The Sierra Nevada NPS I&M Network, for example, is using the PACE approach to define an ecologically meaningful regional context for a Natural Resource Condition Assessment underway at Sequoia and Kings Canyon National Parks. Similarly, Badlands National Park is organizing its climate change assessment within PACE boundaries. NPScape, the NPS I&M landscape dynamics monitoring project, is interested in using PACEs for reporting at a landscape scale the natural systems, anthropogenic drivers, and conservation context of all 270 park units with significant natural resources. In a related project, we have defined PACEs around a total of 60 US park units and quantified land use and climate change in them as a basis for assessing vulnerability to future change (Davis et al in prep, Haas et al. in prep). We encourage the USNPS to evaluate this approach and where appropriate to use it for all ecologically-significant park units. Applications to other US federal lands could be facilitated through the emerging USDOI Landscape Conservation Cooperatives (LCCs) established by DOI Secretarial Order 3289. Currently, the Great Northern LCC (Northern Rocky Mountains) is considering using the PACE approach as a basis for analysis for all of its protected areas (T. Olliff, pers. comm). Internationally, the PACE framework could be applied within countries by national protected area management agencies and across networks of countries by collaborations among national entities and nongovernmental organizations with active conservation programs. DeFries et al. (2010a,b) demonstrated using a similar approach for six protected areas in the humid tropics. To the extent that the PACE approach is employed internationally, a central database of PACE

boundaries, such as in the IUCN Protected Areas Database (IUCN 2003) would make the boundaries widely available and thus help facilitate monitoring, evaluation, and conservation.

In conclusion, it has long been recognized that many protected areas are incomplete subsets of larger surrounding ecosystems that are often unprotected and vulnerable to human impacts. Before and since the creation of the USNPS, park managers have advocated for park expansion and/or the creation of protective buffer zones, however during the 1980s private land rights issues made these positions politically untenable. Using modern ecological theory, extensive spatial datasets, and geospatial analysis hardware and software, we have illustrated a comprehensive and scientifically defensible approach to delineating PACE boundaries. Maturation of incentive-based approaches to conservation in recent decades may now allow key locations within PACEs to be managed so as to better maintain ecological condition in areas adjacent to protected areas. The need to identify, monitor, study, and conserve PACEs is crucial now as land-use intensification threatens many of the world's protected areas.

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Author Biographies

Andrew J. Hansen (hansen@montana.edu) is a Professor in the Ecology Department and Director of the Landscape Biodiversity Lab at Montana State University. His research focuses on land use change and its consequences on protected areas. Cory R. Davis is currently a PhD student at Montana State University studying land use changes surrounding US national parks and how they may impact biodiversity within the parks. Nathan Piekielek is a PhD student at Montana State University studying decision support for protected area managers and land use effects on primary productivity. John Gross is an Ecologist with the National Park Service's Inventory and Monitoring (I&M) Program. He provides science support to NPS I&M Networks and coordinates climate change activities across the NPS. David M. Theobald is a Research Scientist in the Department of Human Dimensions of Natural Resources at Colorado State University. His research focuses on the spatial modeling of landscape change and connectivity. Scott Goetz is a Senior Scientist at the Woods Hole Research Center, Falmouth, Massachusetts. His research focuses on the analysis of environmental change, including monitoring and modeling links between land use change, forest productivity, biological diversity, water quality, and epidemiology. Forrest Melton is a research scientist at California State University Monterey Bay and contractor with the NASA Ames Research Center, Moffett Field, California. His work focuses on the development of ecological forecasting software and applications. Ruth DeFries is the Denning Professor of Sustainable Development in the Department of Ecology, Evolution, and Environmental Biology at Columbia University, New York. She studies human transformation of the landscape and its consequences for climate, biogeochemical cycling, biodiversity, and other ecosystem services.

Author Contributions

Andrew Hansen helped develop the approach for linking protected areas to their surroundings, the methods used for defining the appropriate area, and was lead author of the manuscript. Cory Davis and Nathan Piekielek helped develop the methods for delineating PACE boundaries, performed spatial analyses, and helped draft and review the manuscript. John Gross provided insight into how park management and resources interact with surrounding communities, gave input on methods and data sources, coordinated contact with NPS staff, and provided review of the manuscript. David Theobald helped develop the methods for delineating PACE boundaries, provided data for analyses and provided input and review for the manuscript. Scott Goetz and Forrest Melton helped conceptualize the approach to PACE delineation and provided review of the manuscript. Ruth DeFries helped conceptualize the approach of the analysis and provided review of the manuscript.

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Table 1. USDI National Park Service units included in this study, their locations, and the PACE mapping criteria that were uniquely applied to the units. The watershed, contiguous habitat, and human edge effect criteria were applied to all of the park units.

Park units	Park code	Location	Unique mapping criteria	
			Disturbance	Crucial habitats
North Cascades National Park Complex	NOCA	Northwest Washington	Historic fire records	Salmon
Olympic National Park	OLYM	Western Washington	Not applied	Salmon, spotted owl, marbled murrelet
Mount Rainier National Park	MORA	Southwest Washington	Not applied	Salmon, mountain goat, cascade fox, wolverine, white-tailed ptarmigan
Yosemite and Sequoia-Kings Canyon National Parks	YOSE/SEKI	Central California	Historic fire records	Great grey owl, Yosemite toad
Yellowstone and Grand Teton National Parks	YELL/GRTE	Northwest Wyoming, Montana,	Historic fire records	Elk and pronghorn antelope winter range and migration routes, bird source areas
Big Horn Canyon National Recreation Area	BICA	North-central Wyoming, south-central Montana	Not applied	Not applied
Rocky Mountain National Park	ROMO	North-central Colorado	Not applied	Ungulate winter range, raptor foraging,
Big South Fork National River and Recreation Area	BISO	South-central Kentucky, north-central Tennessee	Not applied	Endangered fish species
Great Smoky Mountains National Park	GRSM	Eastern Tennessee, western North Carolina	Not applied	Not applied
Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River	DEWA/UPDE	Eastern Pennsylvania, northwestern New Jersey	Not applied	Shad, amphibians, endangered bivalve

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Table 2. Spatial characteristics (in km²) of protected area centered ecosystems (PACEs) and polygons derived for each criterion.

Park units	Park area	PACE outside park	PACE/ park ratio	Area of PACE criterion outside park (% unique)					% with 2 or more criteria
				Contiguous habitat	Watershed	Disturbance	Crucial habitats	Human edge effects	
NOCA	2756	13,395	4.9	12,076 (43)	4233 (1)	800 (0)	1749 (4)	579 (0)	51
OLYM	3700	12,385	3.3	12,221 (33)	4408 (0)	---	2199 (0)	4218 (1)	67
MORA	952	8062	8.5	3736 (10)	1644 (1)	---	4138 (25)	2585 (9)	48
YOSE/ SEKI	6530	32,360	5.0	142,886 (0)	4292 (0)	31,441 (27)	7262 (3)	36,570 (0)	57
YELL/ GRTE	10,159	32,362	3.2	24,876 (0)	12,881 (1)	32,158 (12)	13,758 (1)	4730 (3)	78
BICA	484	31,370	64.8	6906 (4)	29,161 (73)	---	---	4074 (1)	20
ROMO	1080	9450	8.8	6768 (43)	1690 (0)	---	1398 (0)	1986 (10)	35
BISO	471	7505	15.9	5515 (18)	2782 (3)	---	399 (4)	4627 (11)	61
GRSM	2098	13,627	6.5	10,600 (40)	3558 (0)	---	---	6464 (13)	46
DEWA/ UPDE	432	14,046	32.5	7597 (2)	10,826 (22)	---	725 (0)	9282 (10)	63
Mean	2866	17,456	15.3	23318	7547	21,466	3953	7511	52

Figure Legends

Figure 1. Framework for delineating protected area centered ecosystems using data available for the U.S.

Figure 2. Maps of protected-area centered ecosystems delineated in this study for 13 US National Park units. Gradations in color in the PACEs outside of the parks indicate the number of overlapping classification criteria. Places with many overlapping criterion may be considered more important for monitoring and management

Figure 3. Location of the protected area centered ecosystems along gradients in land ownership and land development (home densities of >0.031 units/ha, roads, or agriculture lands) (left) and home density (units/ha) and percent change in home density from 1940 to 2000 (right).

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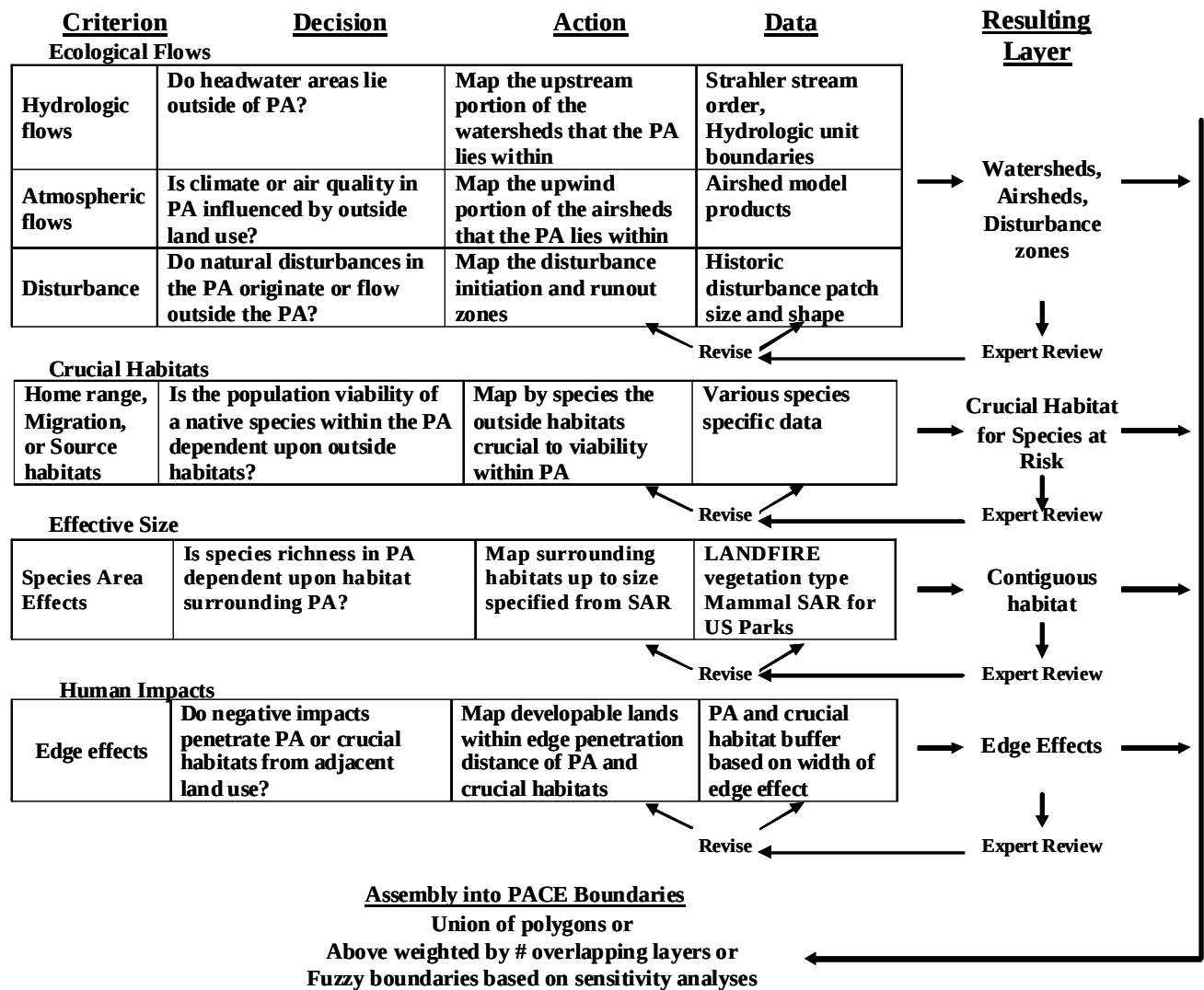


Figure 1.

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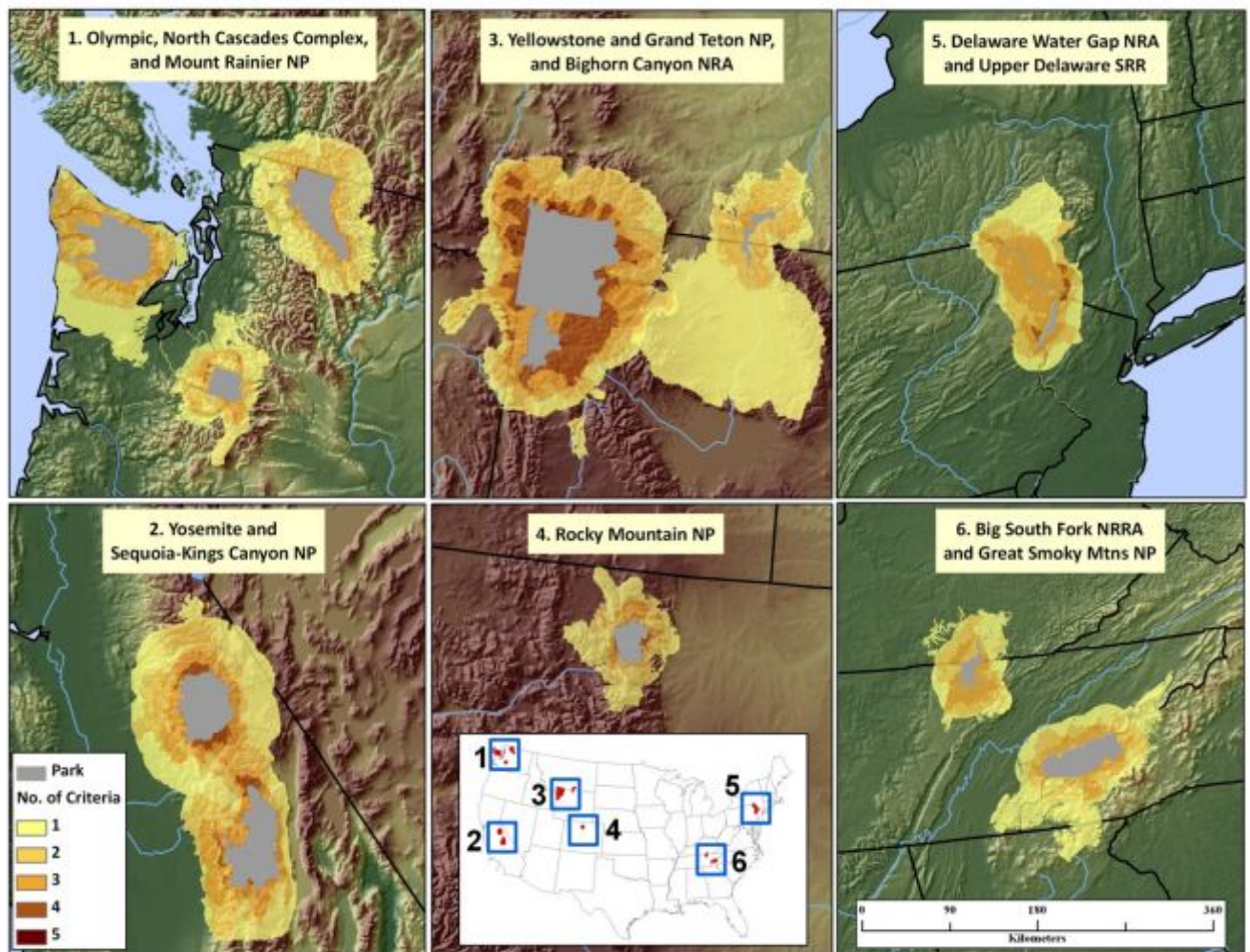


Figure 2

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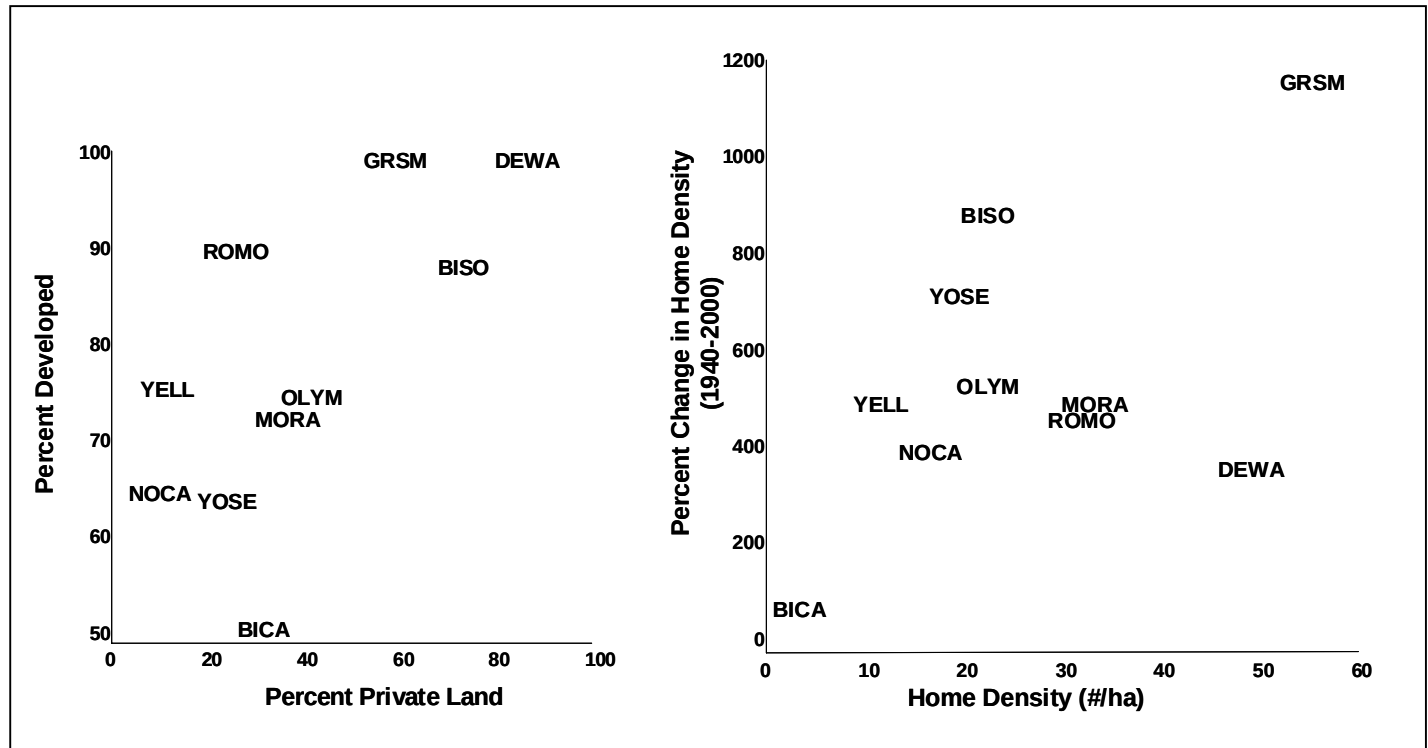


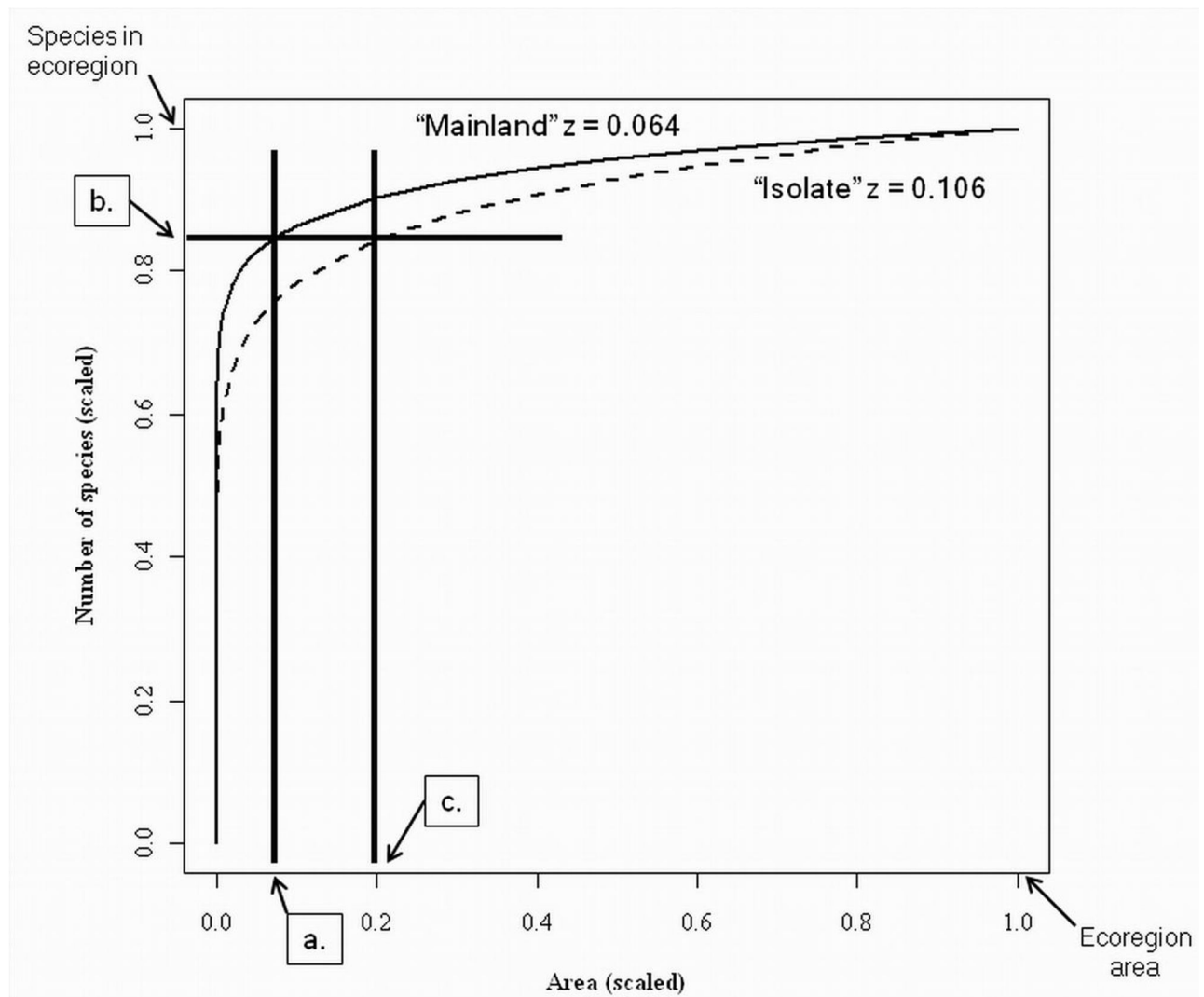
Figure 3

Appendix I: Details of Methods

Develop framework for delineation. We drew on the mechanisms described in Hansen and DeFries (2007) to develop criteria for mapping PACE boundaries (Table 1). These mechanisms are the primary means by which land use in surrounding lands influences ecological processes and the viability of native species within protected areas. The objective was to map the spatial domain of the area of strong effects between each criterion and the protected area. The polygons generated to best represent each criterion were then combined to define the PACE boundary. Initially we drew on datasets available for the contiguous US and supplemented these with data received from specific parks. Below, we describe specific datasets and decision rules that we recommend for delineating PACEs. We also point out alternative decision rules that might be more appropriate in some situations.

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Criterion 1: Watershed Boundaries. Watersheds were derived from the hydrological units delineated in the Watershed Boundary Dataset developed by the US Department of Agriculture Natural Resources Conservation Service (NRCS), the US Geological Survey (USGS), and the US Environmental Protection Agency (USEPA 2005). Hydrologic units are subdivisions of watersheds nested from largest to smallest areas and are used to organize hydrologic data. These have been mapped across the US at the subbasin (8-digit), watershed (10-digit), and subwatershed (12-digit) levels. We selected these levels in the hierarchy of hydrologic units based on stream order as defined in the Strahler system (USEPA 2005). Subwatersheds are used for streams of order 1-3. Watersheds are used for streams of order 4-6. Subbasins are used for streams of orders 7-10. Appropriately-sized hydrological units were selected for all streams that intersected the protected area, unless they were considered to be isolated from the park by dams. Additional upstream units were selected if deemed particularly influential by park staff. Decisions about inclusion of hydrological units downstream of the protected area were based on movements of individual species (see Criterion 4).

Criterion 2: Airshed Boundaries. Unlike watersheds, national maps of airsheds are not currently available. Regionally, airsheds have been defined with regards to flows of pollutants. The Georgia Basin / Puget Sound Airshed, for example, was defined as an area where the movement of air (and, therefore, air pollutants) can be hindered by local geographical features such as mountains, and by weather conditions (British Columbia Ministry of Environment 2010). The Chesapeake Bay airshed was defined by the USEPA as the area containing the air emission sources contributing 75 percent of the nitrogen deposited from the air to the Bay and its watershed (USEPA 2010). Airsheds for protected areas could be delineated similarly based on the location of sources of pollutants deposited into the protected area. Spatially-explicit pollution models can be used to derive such maps (Kinnee et al. 1997). Airsheds could also be defined to include locations where human land use is known to cause changes in climate within a protected area, as is the case in Monte Verde National Park in Costa Rica (Lawton et al. 2001).

Criterion 3: Disturbance Initiation and Runout Zones. Historic datasets were used to map the boundaries of potential disturbance initiation and runout zones (Baker et al. 1992) for protected areas which experience contagious disturbances (e.g., fire, flooding, insect infestations). The general approach was to use data on past disturbance location, size, and shape to identify the area surrounding the protected area that would include disturbance events up to the 95th percentile (by area) that intersected the park during the historic record. This mapping identifies the areas outside the protected area from which disturbance moved into the protected area or that disturbance moved to after leaving the protected area. We did not want to include disturbance events that were very infrequent and very large because the resulting PACE boundary would be very large and not strongly linked to the protected area. Thus we omitted consideration of the largest 5% of disturbances in the historic record. The disturbance data should come from the time prior to land use change and represent the period when disturbance functioned in ways that maintained protected area condition. National historic data on such disturbances are not available, hence the best available local data must be considered for each protected area. In the case of fire, the method was to use historic fire maps to estimate the 95th percentile large fire area by fire regime group (which is defined across the US in USDOJ 2006). The mean fire area shape

was also calculated to determine run-out length. Fire regime groups were weighted based on historical fire size and shape and a threshold is established to represent a 95th percentile fire event for each fire regime group. For example, if there was a documented history of especially large or linear fires occurring in a given fire regime group it is assigned a low weight to represent little impedance to disturbance travel through these areas. The calculated mean large fire threshold was then applied to the protected area boundary in all directions using cost-weighted distance analysis in ARCGIS 9.2. The resulting disturbance area was meant to represent a conservative estimate of areas which could be connected by disturbance to the protected area across a range of environmental conditions. A similar method could be used for flooding, based on, for example, 100-year flood event maps.

Criterion 4: Crucial Habitats. The PACE should be of sufficient size such that self-sustaining populations of species with habitat requirements not met within the protected area can be maintained within the PACE. Typically, species-specific quantitative data are available only locally or for a limited number of species. Such data and/or local expert opinion were used to identify and map crucial habitats outside of the protected areas that are required by populations within protected areas during important seasonal or life-history stages. Examples of such habitats were dry-season or winter habitats, population source areas, movement corridors, or areas used by species with large home ranges.

Criterion 5: Contiguous Habitats. The habitat requirements and movements of many organisms are not known adequately to quantify crucial habitats surrounding a protected area. A “coarse filter” approach (Noss and Cooperrider 1994) to deal with these lesser-known species was based on species-area relationships. The number of species within a protected area is influenced by its size and by its connectivity to adjacent habitats. An “isolated” protected area is expected to have fewer species than one embedded in a larger area of contiguous habitat (Cowlshaw 1999, Brooks et al. 1999). The goal was to determine the area of contiguous habitat surrounding a protected area that is required to prevent the loss of species from the protected area due to isolation by destruction of surrounding habitats.

To determine which habitat types to include and where on the surrounding landscape this area should be placed, a cost-weighted distance analysis (nearer habitats were favored) in ARCGIS 9.2 was used to select vegetation community classes outside of the protected area that were similar to those within the protected area. This was done by weighting vegetation classes based on their proportional representation within the protected area such that classes with higher proportional abundance were favored. The assumption is that species populations within the protected area will require similar habitat types outside of the protected area. Seasonal habitat use and migration habitat are addressed in the crucial habitat criteria.

A GIS-based model preferentially selected pixels of vegetation types of higher proportional abundance in the protected areas and nearer to the protected areas. Cost values for developed areas and agricultural classes were artificially inflated to discourage the model from selecting those areas. In cases where managers desired inclusion of rare habitat types that were thought to be of high value, weights for these types were altered to favor their selection. We used the Existing Vegetation Type layer from the LANDFIRE program (USDOI 2006) to represent currently existing vegetation community classes. NatureServe developed these data using a model containing a combination of field data, satellite imagery, biophysical gradient layers, and regression classification methods (Comer et al.

2003). This data set has 469 classes at a resolution of 30 m and is organized hierarchically such that classes can be combined as is deemed appropriate for a particular application.

The size of contiguous habitats required to maintain species within parks can be estimated based on the species-area relationship and species richness data from national parks. In a similar manner as did Brooks et al. (1999), we used the relationship between isolated protected areas and non-isolated protected areas to estimate this size. Brooks et al. estimated the number of species expected to be lost as a habitat was fragmented due to reduction in area and increased isolation from similar habitats. They assumed that the total species in the original habitat would be reduced due to loss of area as predicted by the species-area relationship for mainland areas.

$$S = cA^z$$

where S is the number of species present within a given area, A , and c and z are constants (Rosenweig 1995). The constant z is the primary determinate of the slope of the curve and hence rate of species loss. Brooks et al. (1999) summarized data for progressively larger areas of continuous habitat (i.e. mainlands) and found an average z of 0.15. The estimated number of species in the habitat fragment was further reduced due to the effect of isolation based on the species area relationship for islands (assumed to be isolated), which have an average z value of 0.25 (Rosenweig 1995).

Brooks et al. derived the area of the habitat before fragmentation (A_{total}) from historic maps and aerial photos and the number of species in this area (S_{total}) from field samples and museum records. Area of current habitat fragments was derived from current aerial photos. The number of species in the fragment prior to fragmentation ($S_{original}$) was estimated using a z value of 0.15 and the equation:

$$S_{original}/S_{total} = (A_{fragment} / A_{total})^z$$

The number of species expected to be in the fragment after full isolation ($S_{fragment}$) due to destruction of surrounding habitats was estimated with the equation:

$$S_{fragment}/S_{total} = (A_{fragment} / A_{total})^z,$$

where z was set to 0.25 as found on islands.

We first estimated the species-area relationship assuming protected areas were not isolated. This curve is derived from data from 57 large (> 28,000 ha) US national parks selected for wide geographical distribution relative to climate and land use gradients, and that are managed for natural values or biodiversity. The log-log form of the species-area equation was used to plot log species versus log area:

$$\log S = \log c + z \log A$$

The number of non-flying mammal species within each park (USNPS 2008) was plotted against park area. Non-flying mammals were used because they are present in a wide-range of habitats

and latitudes, include species that require large home ranges, and are reasonably well surveyed in our geographic region. We did not include birds or bats because of their ability to migrate long-distances and move across land-use barriers. Reptiles and amphibians were not used because they are largely restricted to southern latitudes of the US and because their high fecundity rates allow populations to persist in relatively small areas. The resulting z value was 0.0636 and was assumed to approximate the slope of the species-area relationship for these parks assuming they are currently in a non-isolated state. We recognize that some of the parks may be more isolated now than when they were created but our goal was to determine the area required to maintain all species currently existing in the parks.

We assumed that the potential total number of species in a park was that found in the ecoregion (Olsen et al. 2001) containing the park. We scaled the area of each park to the area of the surrounding ecoregion (figure 2). We then used the park species-area relationship to estimate the number of species expected to be present in each individual park if not isolated based on the derived species-area relationship. We derived a slope for the species-area curve for isolated parks based on the proportion of z for mainlands and islands used by Brooks et al. (1999):

$$0.15/0.25 = \text{non-isolate slope/isolate slope};$$

which in our case is:

$$(0.06)*(0.25)/(0.15) = 0.10$$

We used this relationship to estimate how large an isolated park needs to be to support the current number of species found within that park. This area was then used as the target size for running the contiguous habitat model mentioned above. The result identifies contiguous habitat around each park needed to support species presently found within the park.

As demonstrated by Brooks et al. 1999, isolation of protected areas by habitat destruction on surrounding lands can substantially reduce species richness within protected areas. Thus, we feel it is important to consider areas of contiguous habitat in defining the PACE. Nonetheless, objectively determining the size of surrounding habitats required to maintain species richness with protected areas is very challenging due to data limitations and other factors. The method described above is our best attempt to meet this goal. However, the method is based on several assumptions.

-) The slope of the species area relationship we derived for 57 US parks is applicable to the individual parks it was applied to in this study.
-) The species area relationship for non flying mammals used in this study is representative of this relationship for other taxonomic groups.
-) Protected areas are representative subsets of the surrounding ecoregion in terms of species richness.
-) The distribution of current vegetation types in and around the protected area is adequate to maintain current species richness within the protected area.
-) The ratio of 0.15/0.25 derived by Brooks et al. (1999) to represent the difference in slope between non-isolate and isolated habitats is appropriate to our application to protected areas.

It is difficult to determine how well these assumptions are met and we suspect there is high uncertainty in the resulting contiguous habitat layers derived in this study. Hence, we

suggest the contiguous habitat criterion be used with recognition of this higher level of uncertainty than for the other criteria. Individual protected areas are also encouraged to alter the weighting of habitat classes in the model according to perceived vegetation importance (e.g. rare habitat types) and to incorporate areas of important habitat not identified in the model via other criteria (e.g. crucial habitats).

Criterion 6: Human Edge Effects. The extent to which human activities outside a protected area may penetrate into adjacent protected areas varies with activity and social and biophysical setting. Examples are 0 to 500 m for changes in microclimate at human induced forest edge (Harper et al. 2005), 83 to 130 m for human trampling and firewood gathering in suburban forest fragments (Matlack 1993), at least 6 km for brood parasite effects on host bird species (Hansen and Rotella 2002), and up to 25 km for poaching in East Africa (Campbell and Hofer 1995). Selection of buffer distance must be subjective when quantitative data are not available. One choice is to select a distance that exceeds any known edge penetration distance. Another is to use buffer widths that bracket the most likely maximum distance based on uncertainty analyses. Our framework uses a buffer of 25 km around the protected area, to exceed known edge penetration distance. Within this area all private, non-protected land was selected. Additionally, we included a 5-km buffer around private lands that lay outside the 25-km buffer but within polygons from the previous 5 criteria for defining PACEs. Edge effects from land-use intensification in this 5-km buffer could degrade crucial habitats and ecological processes that are more distant from the protected area, hence they are included in the PACE boundaries. The 5-km distance was selected to include the maximum distances of most of the known edge penetration distances but not to dramatically increase the size of the PACE.

The maps derived for each criterion were then reviewed by local experts for accuracy and completeness. The review comments may lead to changes to the mapping approach or the datasets used in a second iteration of boundary mapping. The final maps for each criterion were combined to delineate the PACE. Various methods can be used to join the maps depending on local ecological, socioeconomic, or political factors. These include: taking the union of the individual polygons; weighting the importance of locations within the union based on number of criteria represented; and deriving the boundaries for the individual criterion using assumptions that bracket uncertainty in key parameters and representing this uncertainty with “fuzzy” PACE boundaries.

Apply Framework. We applied the methods to 13 US park units administered by the USNPS (Table 2). The study area was confined to the contiguous US to increase consistency of biophysical datasets. Our goal was to include a representative subset of NPS units to demonstrate proof of concept and lay the foundation for application of the approach to additional USNPS units and other protected areas. Criteria for selection were: wide geographic, ecoregional, and physiognomic distribution; diverse land allocation types in surrounding areas; variation in park size and shape; and concentration within relatively few USNPS Inventory and Monitoring (I&M) networks to facilitate coordination with USNPS personnel. An initial map was made using national datasets for the watershed, contiguous habitat, and human edge effect criteria. Consultation with local USNPS I&M staff and park scientists was used to evaluate the airshed, disturbance, and crucial habitat criteria. The final maps were developed through two cycles of sending initial maps and description of methods to local NPS scientists and modifying based on their comments.

We assessed the sensitivity of each PACE to individual criteria by quantifying the percentage of the PACE that was uniquely covered by each individual criterion. The area covered by each criterion was compared to the area covered by the union of all other criteria. If a given criterion lies entirely within the union of all other criteria this value is 0%. If a given criterion covered the union of all other criteria and an equal amount of area outside the union of all other criteria, the value is 50%. In cases where this percentage is high for one of a few criteria (e.g. these criteria contribute uniquely and heavily to the final PACE boundary), the assumptions underlying the mapping of this criterion should be more carefully scrutinized. In cases where percentage is low for all criteria, this indicates substantial overlap among the criteria and the PACE boundary is less sensitive to the assumptions of one or a few criteria. We also quantified the percent of the PACE that is covered by two or more criteria.

The watershed, contiguous habitat, and human edge effect criteria were applied to all of the park units (Table 3). Atmospheric transport of nutrients and pollutants has a clear potential to impact park units and we retained the airshed criterion in our framework, however, airshed data were inadequate at present for all parks evaluated, hence it was not applied to any parks in the current analysis. The disturbance criterion was applied to North Cascades National Park Complex, Yosemite and Sequoia-Kings Canyon National Parks and Yellowstone and Grand Teton National Parks where fire is an important disturbance and the required data were available. The species for which crucial habitats were considered varied by park unit and were largely identified during the expert review phase. Winter range and/or migration routes of ungulates were included in several parks (Mount Rainier National Park, Yellowstone and Grand Teton National Parks, Rocky Mountain National Park). Two wilderness areas adjacent to Mount Rainier National Park were included as crucial habitat or corridors for several species including mountain goats, cascade fox, wolverine, and white-tailed ptarmigan. Birds were included in Yellowstone and Grand Teton National Parks (bird population source areas) and Rocky Mountain National Park (raptor foraging areas). A layer of late-successional old growth forest, which is crucial habitat for many species including spotted owls and marbled murrelets was included for Olympic National Park. Amphibian habitats were used in Yosemite and Sequoia-Kings Canyon National Parks and Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River. Crucial river stretches for migrating fish species were also included: salmon runs in Mount Rainier National Park, North Cascades National Park Complex, and Olympic National Park, shad runs in Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River, movement of several species of endangered fish in Big South Fork National River and Recreation Area. All rivers were buffered by 400 meters which is the distance recommended for protection of Wild and Scenic Rivers.

Evaluation of PACEs. We evaluated the characteristics of PACEs that may influence the challenge of maintaining ecological condition within national parks. These characteristics included:

- ☐ Ownership – proportion of PACE area in public versus private ownership
- ☐ Proportion developed – percentage of the private lands in agriculture, near roads, or with home densities that exceeded a minimum threshold
- ☐ Home density – total number of homes in 2000 (most recent census)
- ☐ Change in home density – percentage change in home density from 1940 to 2000

Ownership classes were primarily derived from the Protected Area Database v4.6 (IUCN 2003) with some additional datasets to provide more recent data on protected lands. Lands privately owned and not in a conservation easement are termed here “private lands unprotected”. Percent of private lands that were developed in 2000 (date of last census) were defined as the sum of areas of roads (US Census Bureau 2009), agriculture lands (USGS 2005), and areas with home densities of greater than 0.031 units per hectare all divided by the total area of private land. Areas with home densities below this threshold are assumed to be little influenced by land use (Theobald 2005). The home density data were from Theobald (2005) who down-scaled home density estimates from US Census blocks to a 1 km resolution based on groundwater well density, accessibility to urban areas along roads, land-cover characteristics, and other factors for the period 1940-2000. Home density across the private lands of the PACE was estimated by multiplying the midpoint of each home density class times the area of private land in that class. Classes, home density range (units per hectare), and midpoints were: undeveloped and low rural, 0.001-0.031, 0.015; rural, 0.031-0.063, 0.047; exurban, 0.063-1.45, 0.757; suburban and urban, 1.45 to >4.12, 2.785. Roads layers were used to identify developed areas by including buffers of 5 to 15 m based on their level of use and following the work of Forman (2000). Percent change in number of homes was estimated by subtracting number of homes in 1940 from that in 2000, dividing by number in 1940, and multiplying by 100.

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PALMS

Park Analysis of Landscapes and Monitoring Support

Table 1. Criteria used to delineate protected area centered ecosystem boundaries and the ecological mechanisms on which they are based. The mechanisms are means by which human activities on surrounding lands may alter ecological processes and/or the viability of native species within protected areas (adapted from Hansen and DeFries 2007).

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Mechanism	Ecological effects	Goal for monitoring and management	PACE delineation criterion
Change in ecological flows into and out of protected area	Water, sediment, nutrients, and organisms move with water flows through watersheds. Land use in upper watersheds may alter these flows into protected area	Maintain natural aquatic inputs to protected area	Watershed boundaries: basins, intersecting protected area.
	Land use upwind in airshed changes climate, pollution levels in protected area	Maintain natural climate and air quality in protected area	Airsheds defined based on pollution or climate
	Disturbances (e.g. fire) may originate outside and move through a protected area. The condition of the disturbance initiation zone influences the likelihood of disturbance moving into the protected area. Runout zones may provide important habitat for organisms in the protected area	Identify and maintain ecological process zones	Perimeter around protected area of potential disturbance initiation and runout zones based on historic disturbance size and shape
Loss of crucial habitats	Seasonal habitats, population source areas, movement paths, or portions of large home ranges for populations within protected areas may lie outside the protected areas. Land use may alter or destroy these crucial habitats.	Maintain key unprotected habitats	Migration, source-sink, and seasonal habitats of protected-area based organisms
Change in effective size of reserve	Species within a protected area can be lost due to isolation as the area	Maintain adequate area of habitat around protected area to prevent	Habitat types in proportional representation up to size specified from

Table 2. USDI National Park Service units included in this study and their location and setting.

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Park units	NPS I&M network	Location	Ecoregion(s)	Physiognomic setting
North Cascades National Park Complex (NOCA)	North Coast and Cascades	Northwest Washington	British Columbia mainland coastal forests, Cascade Mountains leeward forests	Mountain, upper to mid watershed
Olympic National Park (OLYM)	North Coast and Cascades	Western Washington	Central Pacific coastal forests, British Columbia mainland coastal forests	Mountain, upper to lower watershed
Mount Rainier National Park (MORA)	North Coast and Cascades	Southwest Washington	Central and southern Cascades forests	Mountain, upper watershed
Yosemite and Sequoia-Kings Canyon National Parks (YOSE/SEKI)	Sierra Nevada	Central California	Sierra Nevada forests	Mountain, upper watershed
Yellowstone and Grand Teton National Parks (YELL/GRTE)	Greater Yellowstone	Northwest Wyoming, Montana,	South Central Rockies forests	Mountain, upper and mid watershed
Big Horn Canyon National Recreation Area (BICA)	Greater Yellowstone	North-central Wyoming, south-central Montana	South Central Rockies forests, Wyoming Basin shrub steppe	Plateau and canyon, mid watershed
Rocky Mountain National Park (ROMO)	Rocky Mountain	North-central Colorado	Colorado Rockies forests	Mountain, upper watershed
Big South Fork National River and Recreation Area (BISO)	Appalachian Highlands	South-central Kentucky, north-central Tennessee	Appalachian mixed mesophytic forests	Plateau, mid watershed
Great Smoky Mountains National Park (GRSM)	Appalachian Highlands	Eastern Tennessee, western North Carolina	Appalachian-Blue Ridge forests	Mountain, upper watershed
Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River (DEWA/UPDE)	Eastern Rivers and Mountains	Eastern Pennsylvania, northwestern New Jersey	Allegheny Highlands forests, Appalachian-Blue Ridge forests	Lowland, mid-watershed

PALMS

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Park code	Criterion					
	Watershed a	Airshed	Disturbanc e	Crucial habitats	Contiguou s habitats ^b	Human edge effects ^c
NOCA	Watersheds , subwatersh eds	Not applied	Historic fire records	Salmon	68/74/184,2 01	25-km buffer
OLYM	Watersheds , subwatersh eds	Not applied	Not applied	Salmon, spotted owl, marbled murrelet	64/82/211,6 13	25-km, 5- km buffers
MORA	Watersheds , subwatersh eds	Not applied	Not applied	Salmon, mountain goat, cascade fox, wolverine, white-tailed ptarmigan	59/82/44,95 0	25-km, 5- km buffers
YOSE/ SEKI	Watersheds , subwatersh eds	Not applied	Historic fire records	Great grey owl, Yosemite toad	79/87/52,87 2	25-km, 5- km buffers
YELL/ GRTE	Watersheds , subwatersh eds	Not applied	Historic fire records	Elk and pronghorn antelope winter range and migration routes, bird source areas	67/86/159,6 93	25-km, 5- km buffers
BICA	Subbasins	Not applied	Not applied	Not applied	63/93/374,1 99	25-km buffer
ROMO	Watersheds	Not applied	Not applied	Ungulate winter range, raptor foraging,	61/86/132,8 41	25-km, 5- km buffers
BISO	Subbasin	Not applied	Not applied	Endangere d fish species	54/58/192,2 64	25-km buffer
GRSM	Watersheds	Not applied	Not applied	Not applied	77/77/159,3 43	25-km buffer
DEWA/ UPDE	Subbasins	Not applied	Not applied	Shad, amphibians, endangered bivalve	44/59/243,3 53	25-km, 5- km buffers

Table 3. Data sets used delineate PACE boundaries in for each of the National Park units.

PALMS

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a Subbasins = 8-digit HUCs, watersheds = 10-digit HUCs, and subwatersheds = 12-digit HUCs.

b Numbers used to calculate the area in which contiguous habitat was modeled and represent: number of mammal species in park/ mammal species in ecoregion/ area of ecoregion.

c All private land within 25-km buffer of parks was selected for all parks, for parks with terrestrial crucial habitat all private land was selected within a 5-km buffer.

Figure Legends

Figure 1. Example for Yellowstone National Park of the method used to estimate the size of contiguous habitats outside of the park needed to maintain species in the park. a. Scale park area to ecoregion area: $10255/159693 = 0.0636$. b. Find estimated proportion of total species on “mainland” curve for this area: $S = A^{.096} = 0.0636^{.0636} = 0.839$. c. Find estimated greater ecosystem area on “isolate” curve generated using equivalent proportion as .15/.25: $S = A^{.106} = 0.839^{(1/.106)} = 0.1915$. d. Multiply by ecoregion area: $0.1915 \times 159693 = 30580$ km². This area is three times larger than the area of Yellowstone National park.