Why we need tools to map and value ecosystem services

Introduction

Ecosystems, if properly managed, yield a flow of services that are vital to humanity, including the production of goods (e.g., food), life support processes (e.g., water purification), and life fulfilling conditions (e.g., beauty, recreation opportunities), as well as the conservation of options (e.g., genetic diversity for future use). Despite its importance, this natural capital is poorly understood, scarcely monitored, and—in many cases—undergoing rapid degradation and depletion. To bring understanding of nature's values into decisions, the Natural Capital Project is developing models that quantify and map the values of ecosystem services. The modeling suite is best suited for analyses of multiple services and multiple objectives. The current models, which have low data requirements relative to more complex tools, can identify areas where investment may enhance human well-being and nature. We are continuing to refine existing models and to develop new ones.

We use the Millennium Ecosystem Assessment (2005) definition of the term ecosystem services: "the benefits people obtain from ecosystems." Ecosystems incorporate both biotic and abiotic components and we thus consider "ecosystem services" and "environmental services" to be equivalent. Natural capital is the living and non-living components of ecosystems that contribute to the provision of ecosystem services. Capital assets take many forms including manufactured capital (e.g., buildings and machines), human capital (knowledge, experience, and health), social capital (relationships and institutions), as well as natural capital.

Who should use InVEST?

InVEST is designed to inform decisions about natural resource management. Essentially, it provides information about how changes in ecosystems are likely to lead to changes in the flows of benefits to people. Decision-makers, from governments to non-profits to corporations, often manage lands and waters for multiple uses and inevitably must evaluate trade-offs among these uses. InVEST's multi-service, modular design provides an effective tool for exploring the likely outcomes of alternative management and climate scenarios and for evaluating trade-offs among sectors and services. For example, government agencies could use InVEST to help determine how to manage lands, coasts, and marine areas to provide a desirable range of benefits to people or to help design permitting and mitigation programs that sustain nature's benefits to society. Conservation organizations could use InVEST to better align their missions to protect biodiversity with activities that improve human livelihoods. Corporations, such as consumer goods companies, renewable energy companies, and water utilities, could also use InVEST to decide how and where to invest in natural capital to ensure that their supply chains are sustainable and secure.

InVEST can help answer questions like:

- Where do ecosystem services originate and where are they consumed?
- How does a proposed forestry management plan affect biodiversity, water quality and recreation?
- What kinds of coastal management and fishery policies will yield the best returns for sustainable fisheries, shoreline protection and recreation?
- Which parts of a watershed provide the greatest carbon sequestration, biodiversity, and tourism values?
- Where would reforestation achieve the greatest downstream water quality benefits while maintaining or minimizing losses in water flows?
- How will climate change and population growth impact ecosystem services and biodiversity?
- What benefits does marine spatial planning provide to society in addition to food from fishing and aquaculture and secure locations for renewable energy facilities?

Introduction to InVEST

InVEST is a tool for exploring how changes in ecosystems are likely to lead to changes in benefits that flow to people.

InVEST often employs a production function approach to quantifying and valuing ecosystem services. A production function specifies the output of ecosystem services provided by the environment given its condition and processes. Once a production function is specified, we can quantify the impact of changes on land or in the water on changes on the level of ecosystem service output.

InVEST uses a simple framework delineating “supply, service, and value” to link production functions to the benefits provided to people (Figure 1).

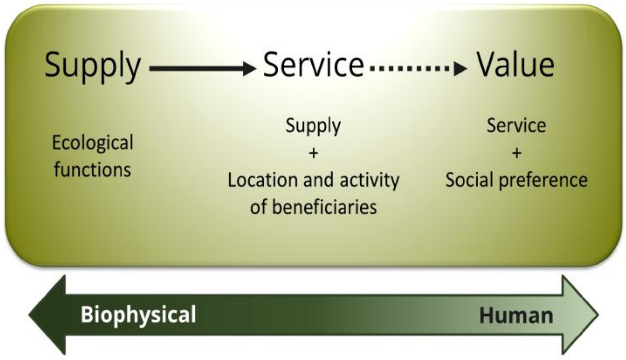

Figure 1: The ecosystem service supply chain, linking ecological function to ecosystem services and the benefits provided to people

“Supply” represents what is potentially available from the ecosystem (ie. what the ecosystem structure and function can provide). For example, this would be the wave attenuation and subsequent reduction in erosion and flooding onshore provided by a particular location and density of mangrove forest. “Service” incorporates demand and thus uses information about beneficiaries of that service (e.g., where people live, important cultural sites, infrastructure, etc.). “Value” includes social preference and allows for the calculation of economic and social metrics (e.g., avoided damages from erosion and flooding, numbers of people affected).

The InVEST toolset described in this guide includes models for quantifying, mapping, and valuing the benefits provided by terrestrial, freshwater, and marine systems. We group models in InVEST into four primary categories: 1) supporting services, 2) final services, 3) tools to facilitate ecosystem service analyses and 4) supporting tools. Supporting services underpin other ecosystem services, but do not directly provide benefits to people. Final services provide direct benefits to people. For final services, we split the services into their biophysical supply and the service to people wherever possible. For some final services, we model the service directly, without modeling the supply separately. Supporting tools include helping to create watersheds, do hydrological processing on a digital elevation model and create scenarios that can be used as inputs to InVEST.

Supporting Ecosystem Services:

- Habitat Risk Assessment
- Habitat Quality
- Pollinator Abundance: Crop Pollination

Final Ecosystem Services:

- Forest Carbon Edge Effect
- Carbon Storage and Sequestration
- Coastal Blue Carbon
- Annual Water Yield
- Nutrient Delivery Ratio
- Sediment Delivery Ratio

- Unobstructed Views: Scenic Quality Provision
- Visitation: Recreation and Tourism
- Wave Energy Production
- Offshore Wind Energy Production
- Marine Finfish Aquacultural Production
- Fisheries
- Crop Production
- Seasonal Water Yield

Tools to Facilitate Ecosystem Service Analyses:

- Overlap Analysis
- Coastal Vulnerability
- InVEST GLOBIO

Supporting tools:

- RouteDEM
- DelineateIT
- Scenario Generator
- Scenario Generator: Proximity Based

Using InVEST to Inform Decisions

Information about changes in ecosystem services is most likely to make a difference when questions are driven by decision-makers and stakeholders, rather than by scientists and analysts. We have found that InVEST is most effective when used within a decision-making process. The Natural Capital Project has used InVEST in over 60 countries worldwide. See the Where We Work section of the NatCap website (https://naturalcapitalproject.stanford.edu/how-do-we-know-it-works/where-we-work/) for the latest map and description of our projects. Through our experience applying InVEST and helping to shape decisions, we have seen how the InVEST tool fits within the larger context of a natural capital approach.

Our approach (Figure 2) starts with a series of stakeholder consultations. Through discussion, questions of interest to policy makers, communities and conservation groups are identified. These questions may concern service delivery on a landscape today and how these services may be affected by new programs, policies, and conditions in the future. For questions regarding the future, stakeholders develop *scenarios* to explore the consequences of expected changes on natural resources. These scenarios typically include a map of future land use and land cover or, for the marine models, a map of future coastal and ocean uses and coastal/marine habitats. These scenarios that are assessed for ecosystem service value by biophysical and economic models that produce several types of outputs. Following stakeholder consultations and scenario development, InVEST can estimate the amount of ecosystem services that are provided on the current landscape or under future scenarios. InVEST models are spatially explicit, using maps as information sources and producing maps as outputs. InVEST returns results in either biophysical terms, whether absolute quantities or relative magnitudes (e.g., tons of sediment retained or % of change in sediment retention) or economic terms (e.g., value of carbon sequestration.)

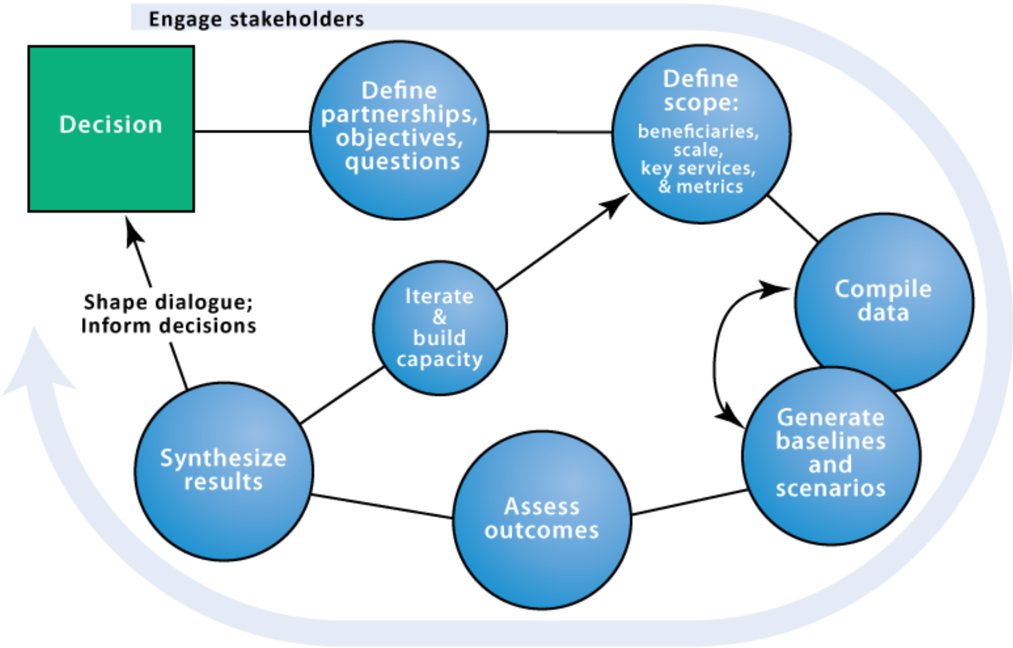

Figure 2: Stages of a natural capital approach to informing decision making.

The spatial extent of analyses is also flexible, allowing users to address questions at the local, regional or global scale. InVEST results can be shared with the stakeholders and decision makers who created the scenarios to inform upcoming decisions. Using InVEST is an iterative process, and stakeholders may choose to create new scenarios based on the information revealed by the models until suitable solutions for management action are identified.

Figure 3 below provides some concrete examples of how the general approach can be used to inform different types of decisions.

Decision context	Define partnerships, objectives, questions	Define scope: beneficiaries, scale, key services & metrics	Compile data	Generate baselines and scenarios	Assess outcomes	Synthesize results	Iterate & build capacity
PES design: Prioritze Water Fund allocations to conservation and restoration projects	Partners: NGOs, water fund participants. Objectives: Improve water quality and secure water supply through watershed conservation and restoration. Questions: Which activities should our fund invest in and where? How much return on our investment will we get?	Beneficiaries: Downstream city municipalities, agri-business, bottling companies; upstream farmers and ranchers. Scale: 50-1000 sq km watersheds with 30m resolution data. Key services & metrics: Kg sediment retained, cubic feet of water produced.	Data: Land-use, DEM, precipitation, soil; pre-processing to translate to erosivity, erodibility, PET, AET; stakeholder input on feasiblity, activity costs	Scenarios: Applying RIOS to select investment portfolio maps (identifying where to promote which activities) for different budget levels, to maximize water quality and quantity; applying to base land-cover to generate scenario maps	Assess outcomes: Run InVEST sediment retention and water yield models on base land-cover and investment scenario maps to evaluate the ecosystem services provided currently and by Water Funds investment	Synthesize results: Graphs or tables ofthe change in ecosystem service provided by current/business-as-usual versus	Iterate & build capacity: Co-develop a tailored tool with NGOs for building investment portfolios; Train water fund platform staff to provide technical support and trainings to others in the region
Infrastructure permitting: Evaluate proposed development project (e.g., mine, road) impacts and offsets	Partners: Local communities, government bodies, NGOs, industry. Objective: Minimize impacts and maximize benefits of development in a socially equitable way. Questions: What are the impacts of proposed development on ecosystem services and how are they distributed among communities?	Beneficiaries: Populations impacted by proposed development and/or mitigation options. Spatial extent: Watersheds or administrative units affected by development project. Services and metrics: For example, carbon sequestration and water-related services are likely to be impacted and important to mitigate, measured as % change in service.	Data: LULC, DEM, biophysical paramteters, soil data, climate data, human population data	Baseline and scenarios: Representing 1) the current landscape, 2) the landscape with development, and 3) the landscape with development and mitigation	Assess outcomes: Quantify climate regulation services (carbon storage) and drinking water quality (sediment and nutrient pollutant loads) across servicesheds before and after development, and with mitigation.	Synthesize results: Graphs and tables showing how much ecosystem services change with development and the amount of impact offset by mitigation. Maps and graphs shoing who is impacted, where the impacts are located and how large any ecosystem service losses are.	Iterate & build capacity: Consider effects of additional mitigation options, provide training to local partners
Corporate supply chain: identify sustainable sourcing strategies	Partners: procurement or R&D divisions of consumer goods corporations. Objective: identify sourcing regions and/or management practices for more sustainable production. Questions: what regions will be able to meet increased demand with minimal impacts on biodiversity and ecosystem services? what management practices should be prioritized in different sourcing regions?	Beneficiaries: Global population, consumers, and/or populations living within sourcing regions. Spatial extent: Ranges, but often municipalities or larger. Services and metrics: Biodiversity, carbon, water, often measured as (relative or absolute) change associated with different sourcing strategies.	Data: LULC, DEM, biophysical paramteters, soil data, climate data, human population data	Baseline and scenarios: Considering how to translate a change in commodity demand to a concomitant change in land-use or land management; or representing different best management practices that could be applied by producers in supply chain	Assess outcomes: Quantify change in biodiversity, carbon storage, and water quality and/or quantity for different sourcing strategies	Synthesize results: Maps of different production patterns and accompanying graphs comparing impacts among different sourcing strategies (regions, assumed patterns of land use/management change)	Iterate & build capacity: Develop detailed guidance and model scripts to facilitate independent runs by corporate sustainability teams to be able to evaluate future soucing decisions in-house
Spatial planning: create a marine spatial plan with zones of use for various activities	Partner: Central agency in charge, clear understanding of participating sectors/jurisdictions Objective: Sustainable delivery of full range of benefits Questions: How can we rationally arrange activities along coast? How might one	Spatial extent: Exclusive economic zone (EEZ), or one bay + watershed. Key services/metrics: Fisheries landings (lbs,$), shoreline protection (area, $), tourism (visitors, $)	Data: Coastline, LULC, bathymetry, coastal habitats, infrastructure, landings, wave/wind	Baseline: Current uses of marine space + current LULC, habitats, etc. Scenarios: Possible future uses of marine space + effect on habitats (can be through habitat risk assessment model)	Assess outcomes: Explore cumulative impacts of activities on habitats, compare landings, storm damages, tourism rates across alternative management schemes	Synthesize results: Create spider diagram showing trade-offs, make maps that highlight differences across management schemes, make bar charts	Iterate & build capacity: Get feedback on results, create new scenarios, train agency staff to run models
Climate adaptation: design and implement a sea-level rise adaptation strategy	Partners: Central agency in charge, clear understanding of participating sectors/jurisdictions Objective: Cost-effectively protect people and property while maximizing co-benefits Questions: Can green infrastructure provide adequate protection? What else does it provide?	Spatial extent: A particular stretch of coastline (e.g. county,bay) Key services/metrics: Shoreline protection (area, $), tourism (visitors, $), carbon sequestered (mT, $) landings (lbs, $)	Data: Coastline, LULC, bathymetry, coastal habitats, infrastructure, landings, wave/wind	Baseline: Current LULC, habitats, seawalls, levees etc. Scenarios: SLR, habitat migration (e.g. from SLAMM), possible adaptation alternatives	Assess outcomes: Compare storm damages, carbon storage, landings, tourism rates across alternative climate/habitat scenarios	Synthesize results: Compare protection provided by alternative scenarios (area, $, people), explore how green infrastructure + grey infrastructure work together, assess /compare co-benefits	Iterate & build capacity: Get feedback on results, create new scenarios, train agency staff to run models

Figure 3: Examples of how the Natural Capital Project has used an ecosystem services approach to inform decisions across a variety of contexts. The columns in this table map onto the stages of the natural capital approach illustrated in Figure 2 above.

A work in progress

InVEST is a free of cost software product licensed under the BSD open source license.

The development of InVEST is an ongoing effort of the Natural Capital Project. We release updated versions of the toolkit approximately every three months that can include updated science, performance and feature enhancements, bug fixes, and/or new models. As a historical note, the original InVEST models were built within ArcGIS but now all models exist in a standalone form directly launchable from the Windows or Mac perating system with no other software dependencies.

A note on InVEST versioning: Integer changes will reflect major changes. For example, the transition from 2.6.0 to 3.0.0 indicates a transition from the Arc-GIS modules to standalone version. An increment in the digit after the primary decimal indicates major new features (e.g, the addition of a new model) or major revisions. The third decimal reflects minor feature revisions or bug fixes with no new functionality.

This guide

This guide will help you understand the basics of the InVEST models and start using them. The next chapter leads you through the installation process and provides general information about the tool and interface.

The remaining chapters present the ecosystem service models. Each chapter:

- briefly introduces a service and suggests the possible uses for InVEST results;
- explains how the model works, including important simplifications, assumptions, and limitations;
- describes the data needed to run the model, which is crucial because the meaning and value of InVEST results depend on the input data;
- provides step-by-step instructions for how to input data and interact with the tool;
- offers guidance on interpreting InVEST results;
- includes an appendix of information on relevant data sources and data preparation advice (this section is variable among chapters, and will improve over time from user input).

Much of the theory related to the scientific foundation of many of these models can be found in the book Natural Capital: The Theory & Practice of Mapping Ecosystem Services (Oxford University Press). The models applied and discussed in that book are not identical to those presented in the InVEST toolset, however, and this user guide provides the most up-to-date description of the current versions of the models. .. primerend

Getting Started

For assistance with installing InVEST on a Mac, see the section Installing InVEST and sample data on your Mac below.

Installing InVEST and sample data on your Windows computer

Download the InVEST installer from http://www.naturalcapitalproject.org. The executable will be called "InVEST_<version>_Setup.exe". Double-click on this .exe to run the installer.

After clicking through the first screen and agreeing to the Licence Agreement, the Choose Components screen will appear. The installer will always install the InVEST Tools and HTML and PDF versions of the InVEST User's Guide. Optionally, sample datasets may also be installed, and by default they are all selected. Note that these datasets are downloaded over the internet, and some are very large (particularly the Marine Datasets), so they make take a long time to install. If you do not wish to install all or some of the sample datasets, uncheck the corresponding box(es).

Next, choose the folder where the InVEST toolsets and sample data will be installed. The installer shows how much space is available on the selected drive. Click Install to begin the installation.

Once installed, the InVEST install folder will contain the following:

- A **documentation** folder, containing the InVEST User Guide in HTML format.
- An **invest-3-x86** folder, containing the compiled Python code that makes up the InVEST toolset.
- **InVEST_<version>_Documentation.pdf**, the InVEST User Guide in PDF format.
- **Uninstall_<version>.exe**, which will uninstall InVEST.
- **HISTORY.rst**, lists of all of the updates included in each new version.

Additionally, shortcuts for all InVEST standalone applications will be added to your Windows start menu under *All Programs -> InVEST |version|*

Advanced Installation

The InVEST windows installer has a number of installation options for several use cases, including silent installation and the use of local sample data. To view the available options, download the installer, open a CMD prompt to the directory that contains the downloaded installer and type:

```
.\InVEST_<version>_x86_Setup.exe /?
```

Standalone InVEST Tools

All of the InVEST models run on an entirely open-source platform, where historically the toolset was a collection of ArcGIS scripts. The new interface does not require ArcGIS and the results can be explored with any GIS tool including ArcGIS, QGIS, and others. As of InVEST 2.3.0, the toolset has had standalone versions of the models available from the Windows start menu after installation, under *All Programs -> InVEST |version|*. Standalone versions are currently available for all models. The ArcGIS versions of InVEST models are no longer supported.

Older InVEST Versions

Older versions of InVEST can be found at http://data.naturalcapitalproject.org/invest-releases/deprecated_models.html. Note that many models were deprecated due to critical unsolved science issues, and we strongly encourage you to use the latest version of InVEST.

Using sample data

InVEST comes with sample data as a guide for formatting your data, and starting to understand how the models work. For instance, in preparation for analysis of your data, you may wish to test the models by changing input values in the sample data to see how the output responds. For the terrestrial/freshwater models it is particularly important that their sample data is only used for testing and example, do not use the spatial data or table values for your own analysis, because their source and accuracy is not documented. Some of the marine models come with global datasets that may be used for your own application - please see the individual User Guide chapters for these models for more information.

Sample data are found in separate sub-folders within the InVEST install folder. For example, the sample datasets for the Pollination model are found in \{InVEST install directory}\pollination\, and those for the Carbon model in \{InVEST install directory}\carbon. For testing the models, you may make a Workspace folder called “output” within the sample data folders for saving model results. Once you are working with your own data, you will need to create a workspace and input data folders to hold your own input and results. You will also need to redirect the tool to access your data and workspace.

Formatting your data

Before running InVEST, it is necessary to format your data. Although subsequent chapters of this guide describe how to prepare input data for each model, there are several formatting guidelines common to all models:

- Data file names should not have spaces (e.g., a raster file should be named ‘landuse.tif’ rather than ‘land use.tif’).
- For raster data, TIFFs are preferred for ease of use, but you may also use IMG or ESRI GRID.
- If using ESRI GRID format rasters, their dataset names cannot be longer than 13 characters and the first character cannot be a number. TIFF and IMG rasters do not have the file name length limitation. When using ESRI GRID as input to the model interface, use the file “hdr.adf”.
- Spatial data must be in a projected coordinate system (such at UTM), not a geographic coordinate system (such as WGS84), and all input data for a given model run must be in the same projected coordinate system. If your data is not projected, InVEST will give errors or incorrect results.

- While the InVEST 3.0 models are now very memory-efficient, the amount of time that it takes to run the models is still affected by the size of the input datasets. If the area of interest is large and/or uses rasters with small cell size, this will increase both the memory usage and time that it takes to run the model. If they are too large, a memory error will occur. If this happens, try reducing the size of your area of interest, or using coarser-resolution input data.
- Similarly, the amount of disk space that is used by the model is in proportion to the resolution of the input data. If the area of interest is large and/or uses rasters with small cell size, this will increase the amount of disk space required to store intermediate and final model results. If not enough disk space is available, the model will return an error.
- Running the models with the input data files open in another program can cause errors. Ensure that the data files are not in use by another program to prevent data access issues.
- Regional and Language options: Some language settings cause errors while running the models. For example settings which use comma (,) for decimals instead of period (.) cause errors in the models. To solve this change the computer's regional settings to English.
- As the models are run, it may be necessary to change values in the input tables. This is usually done with a spreadsheet program like Excel or text editor like Notepad++. Input tables are required to be in CSV (comma-separated value) format, where the values are separated by commas, not semicolons or any other character. If working in Excel, you cannot see the separator, so double-check in Notepad or another text editor.
- Some models require specific naming guidelines for data files (e.g., Habitat Quality model) and field (column) names, which are defined in the User Guide chapter for each model. Follow these carefully to ensure your dataset is valid, or the model will give an error.
- Remember to use the sample datasets as a guide to format your data.

Running the models

You are ready to run an InVEST model when you have prepared your data according to the instructions in the relevant model chapter and have installed the latest version of InVEST.

To begin:

- Review your input data. View spatial data in a GIS, make sure that the values look correct, there are no areas of missing data where it should be filled in, that all layers are in the same projected coordinate system, etc. View table data in a spreadsheet or text editor, make sure that the values look correct, the column names are correct, and that it is saved in CSV format.
- Select the model you wish to run (e.g., Carbon) from the Windows Start menu, and add your input data to each field in the user interface. You may either drag and drop layers into the field, or click the File icon to the right of each field to navigate to your data.
- Inputs for which the entered path leads to a non-existent file or a file that is incorrectly formatted will be marked with a red "X" to the left of the name of the input. If you click the red X, it will give an idea of what is wrong with the data. The model will not run if there are any red Xs.
- Note that each tool has a place to enter a Suffix, which is a string that will be added to the output filenames as *<filename>_Suffix*. Adding a unique suffix prevents overwriting files produced in previous iterations. This is particularly useful if you are running multiple scenarios, so each file name can indicate the name of the scenario.
- When all required fields are filled in, and there are no red Xs, click the **Run** button on the interface.
- Processing time will vary depending on the script and the resolution and extent of your input datasets. Every model will open a window showing the progress of the script. Be sure to scan the output window for useful messages and errors. This progress information will also be written to a file in the Workspace called *<model name>-log-<timestamp>.txt*. If you need to contact NatCap for assistance with errors, always send this log file, it will help with debugging. Also see Support and Error Reporting below for more information.
- Results from the model can be found in the Workspace folder. Main outputs are generally in the top level of the Workspace. There is also an 'intermediate' folder which contains some of the additional files generated while doing the calculations. While it's not usually necessary to look at the intermediate results, it is sometimes useful when you are debugging a problem, or trying to better understand how the model works. Reading the model chapter and looking at the corresponding intermediate files can be a good way to

understand and critique your results. Each model chapter in this User Guide provides a description of these output files.

After your script completes successfully, you can view the spatial results by adding them from the Workspace to your GIS. It is important to look closely and critically at the results. Do the values make sense? Do the patterns make sense? Do you understand why some places have higher values and others lower? How are your input layers and parameters driving the results?

Support and Error Reporting

Several regular training workshops on InVEST may be offered annually, subject to funding and demand. Information on these trainings will be announced on the support page and can be found at the [Natural Capital Project website](). This site is also a good source of general information on InVEST, related publications and use cases and other activities of the Natural Capital Project.

If you encounter any issues when running the models, or have questions about their theory, data, or application, please visit the user support forum at http://forums.naturalcapitalproject.org. First, please use the Search feature to see if a similar question has already been asked. Many times, your question or problem has already been answered. If you don't find existing posts related to your question or issue, or they don't solve your issue, you can log in and create a new post.

If you are reporting an error when running a model, please include the following information in the forum post:

- InVEST model you're asking about
- InVEST version you're using
- What you have already tried to solve the issue, and hasn't worked
- The entire log file produced by the model, located in the output Workspace folder - *<model name>-log-<timestamp>.txt*

Working with the DEM

For the freshwater models SDR, NDR and Seasonal Water Yield, having a well-prepared digital elevation model (DEM) is critical. It must have no missing data, and should correctly represent the surface water flow patterns over the area of interest in order to get accurate results.

Here are some tips for working with the DEM and creating a hydrologically-correct DEM. Included is information on using built-in functions from ArcGIS and QGIS. There are other options for DEM processing as well, including ArcHydro, ArcSWAT, AGWA, and BASINS, which are not covered here. This is only intended to be a brief overview of the issues and methods involved in DEM preparation, not a GIS tutorial.

- Use the highest quality, finest resolution DEM that is appropriate for your application. This will reduce the chances of there being sinks and missing data, and will more accurately represent the terrain's surface water flow, providing the amount of detail that is required for making informed decisions at your scale of interest.

- Mosaic tiled DEM data

  If you have downloaded DEM data for your area that is in multiple, adjacent tiles, they will need to first be mosaicked together to create a single DEM file. In ArcToolbox, use Data Management -> Raster -> Mosaic to New Raster. Look closely at the output raster to make sure that the values are correct along the edges where the tiles were joined. If they are not, try different values for the Mosaic Method parameter to the Mosaic to New Raster tool.

  In QGIS, you can use the Raster -> Miscellaneous -> Merge function to combine the tiles.

- Clipping the DEM to your study area

  We generally recommend that the DEM be clipped to an area that is slightly larger than your area of interest. This is to ensure that the hydrology around the edge of the watershed is captured. This is particularly important if the DEM is of coarse resolution, as clipping to the area of interest will lead to large areas of missing data around the edge. To do this, create a buffer around your area of interest (or watershed) shapefile, and clip the DEM to that buffered polygon. Make sure that the buffer is at least the width of one DEM pixel.

- Reprojecting DEMs

  When reprojecting a DEM in either ArcGIS (Project Raster tool) or QGIS (Warp tool), it is important to select BILINEAR or CUBIC for the "Resampling Technique" in ArcGIS or "Resampling method" in QGIS. Selecting NEAREST (or Near in QGIS) will produce a DEM with an incorrect grid pattern across the area of interest, which might only be obvious when zoomed-in or after Flow Direction has been run. This will create a bad stream network and flow pattern and lead to bad model results.

- Check for missing data

  After getting (and possibly mosaicking) the DEM, make sure that there is no missing data, represented by NoData cells within the area of interest. If there are NoData cells, they must be assigned values.

  For small holes, one way to do this is to use the ArcGIS Focal Mean function within Raster Calculator (or Conditional -> CON). For example, in ArcGIS 10.x:

```
Con(IsNull("theDEM"),FocalStatistics("theDEM",NbrRectangle(3,3),"MEAN"),"theDEM")
```

  Interpolation can also be used, and can work better for larger holes. Convert the DEM to points using Conversion Tools -> From Raster -> Raster to Point, interpolate using Spatial Analyst's Interpolation tools, then use CON to assign interpolated values to the original DEM:

```
Con(isnull([theDEM]), [interpolated_grid], [theDEM])
```

  In QGIS, try the Fill Nodata tool, or the GRASS r.neighbors tool. r.neighbors provides different statistics types, including Mean.

- Identify sinks in the DEM and fill them

  From the ESRI help on "How Sink works": "A sink is a cell or set of spatially connected cells whose flow direction cannot be assigned one of the eight valid values in a flow direction raster. This can occur when all neighboring cells are higher than the processing cell or when two cells flow into each other, creating a two-cell loop."

  Sinks are usually caused by errors in the DEM, and they can produce an incorrect flow direction raster. This can lead to several problems with hydrology processing, including creating a discontinuous stream network. Filling the sinks assigns new values to the anomalous processing cells, such that they are better aligned with their neighbors. But this process may create new sinks, so an iterative process may be required.

  We have found that the QGIS Wang and Liu Fill tool does a good job of filling sinks, and is recommended. You can also use ArcGIS by using the Hydrology -> Fill tool. Multiple runs of Fill may be needed.

- Verify the stream network

  The stream network generated by the model from the DEM should closely match the streams on a known correct stream map. Several of the InVEST hydrology models and the supporting InVEST tool RouteDEM output a stream network (usually called *stream.tif*.) These tools create streams by first generating a Flow Accumulation raster, then applying the user input 'threshold flow accumulation' (TFA) value to select pixels that should be part of the stream network. For example, if a TFA value of 1000 is given, this says that 1000 pixels must drain into a particular pixel before it's considered part of a stream. This is the equivalent of saying that streams are defined by having a flow accumulation value >= 1000.

  Use these *stream.tif* outputs to evaluate how well the modelled streams match reality, and adjust the threshold flow accumulation accordingly. Larger values of TFA will produce coarser stream networks with fewer tributaries, smaller values of TFA will produce more tributaries. There is no one "correct" value for TFA, it will be different for each area of interest and DEM. A good value to start with for testing is 1000.

  To create flow accumulation and stream maps without needing to run a whole hydrology model, you can use the InVEST tool RouteDEM, which is specifically for processing the DEM. See the RouteDEM chapter of the User Guide for more information.

- Creating watersheds

  It is recommended to create watersheds from the DEM that you will be using in the analysis. If a watershed map is obtained from elsewhere, the boundaries of the watershed(s) might not line up correctly with the hydrology created from the DEM, leading to incorrect aggregated results.

  There are a variety of tools that can create watersheds, including the ArcGIS Watershed tool and QGIS Watershed basins or r.basins.fill. InVEST also provides a tool called DelineateIt, which works well, is simple to use, and is recommended. It has the advantage of being able to create watersheds that overlap, such as when there are several dams along the same river. See the DelineateIt section of the User Guide for more information.

  After watersheds are generated, verify that they represent the catchments correctly and that each watershed is assigned a unique integer ID in the field "ws_id" (or "subws_id" if creating sub-watersheds.)

Installing InVEST and sample data on your Mac

Note

In Mac OS 10.13 "High Sierra", InVEST 3.4.0 or later is required.

Numerical results of the Mac binaries may differ slightly (usually within 1e-4) from the results of the Windows binaries. For this reason, we consider InVEST binaries "unstable", but they should still provide reasonable results. As always, if something does not seem to be working, please let us know on the forums: http://forums.naturalcapitalproject.org

Download the InVEST disk image from http://www.naturalcapitalproject.org/invest. The disk image will be called "InVEST <version>.dmg". This image contains a compressed copy of the InVEST executable.

To install:

1. Double-click the disk image to mount it.
2. Drag the folder labeled "InVEST_<version>_unstable" to your Applications folder.
3. Open the InVEST folder you just copied to your Applications folder in a new finder window.
4. The first time you run InVEST, you'll need to do the following:
    1. Right-click on `InVEST.app`, and in the context menu, select *Open*.
    2. In the dialog that pops up, click *Open* once again.
5. In the launcher dialog, select the model you'd like to run and click *Launch*.

The mac distribution includes the executable models and documentation, but unlike the Windows installer does not include sample data. These can be found online at http://data.naturalcapitalproject.org/invest-data/

Scenario Generator: Proximity Based

Summary

The proximity-based scenario generator creates a set of contrasting land use change maps that convert habitat in different spatial patterns. The user determines which habitat can be converted and what they are converted to, as well as type of pattern, based on proximity to the edge of a focal habitat. In this manner, an array of land-use change patterns can be generated, including pasture encroaching into forest from the forest edge, agriculture expanding from currently cropped areas, forest fragmentation, and many others. The resulting land-use maps can then be used as inputs to InVEST models, or other models for biodiversity or ecosystem services that are responsive to land use change.

Introduction

In order to understand the change in biodiversity and ecosystem services (BES) resulting from change in land-use, it is often helpful to start with a scenario or a set of scenarios that exhibit different types of land-use change. Because many of the relationships between landscapes and BES are spatially-explicit, a different pattern of habitat conversion for the same total area of habitat converted can lead to very different impacts on BES. This proximity-based scenario generator creates different patterns of conversion according to user inputs designating focal habitat and converted habitat, in contrast to but potentially complementing the InVEST rule-based scenario generator that creates maps of land-use change according to user-assigned probabilities that certain transitions will occur. Thus, the intent of the InVEST proximity-based scenario generator is not to forecast actual predicted patterns of expansion, but rather to develop different patterns of land use change in order to examine the relationship between land-use change and BES, and how the relationship may differ depending on land use change assumptions.

The model

The tool can generate two scenarios at once (nearest to the edge and farthest from the edge of a focal habitat), for a conversion to particular habitat type for a given area. To convert to different habitat types, different habitat amounts, or to designate different focal habitats or converted habitats, the tool can be run multiple times in sequence.

How it works

Three types of landcover must be defined: 1) *Focal landcover* is the landcover(s) that set the proximity rules from which the scenarios will be determined. The scenario generator will convert habitat from the edge or toward the edge of patches of these types of landcover. This does not mean it will convert these land-covers, only that it will measure distance to or from the edges in designating where the conversion will happen. 2) *Convertible landcover* is the landcover(s) that can be converted. These could be the same as the focal landcover(s), a subset, or completely different. 3) *Replacement landcover* is the landcover type to which the convertible landcovers will be converted. This can only be one landcover type per model run.

Two scenarios can then be run at a time: 1) *Nearest to edge* means that convertible landcover types closest to the edges of focal landcovers will be converted to the replacement landcover. 2) *Farthest from edge* means that convertible landcover types furthest from the edges of focal landcover types will be converted to the replacement landcover. If this scenario is chosen, the user can designate in how many steps the conversion should occur. This is relevant if the focal landcover is the same as the convertible land cover because the conversion of the focal landcover will create new edges and hence will affect the distance calculated from the edge of that landcover. If desired, the conversion can occur in several steps, each time converting the farthest from the edge of the focal landcover, causing a fragmentary pattern.

Below are some examples of the types of scenarios that can be generated by manipulating these basic inputs, using the land-cover in the sample data that ship with this model. This landcover is from MODIS, using the UMD classification (Friedl et al. 2011), which follows the following scheme: 1 – Evergreen needleleaf forest; 2 – Evergreen broadleaf forest; 3 – Deciduous needleleaf forest; 4 – Deciduous broadleaf forest; 5 – Mixed forest; 6 – Closed shrublands; 7 – Open shrublands; 8 – Woody savannas; 9 – Savannas; 10 – Grasslands; 12 – Croplands; 13 – Urban and built-up; 16 – Barren or sparsely vegetated.

Expand agriculture from forest edge inwards:

focal landcover codes: 1 2 3 4 5

convertible landcover codes: 1 2 3 4 5

replacement landcover code: 12

check “Convert From Edge”

number of steps toward conversion: 1

Expand agriculture from forest core outwards:

focal landcover codes: 1 2 3 4 5

convertible landcover codes: 1 2 3 4 5

replacement landcover code: 12

check “Convert Toward Edge”

number of steps toward conversion: 1

Expand agriculture by fragmenting forest:

focal landcover codes: 1 2 3 4 5

convertible landcover codes: 1 2 3 4 5

replacement landcover code: 12

check “Convert Toward Edge”

number of steps toward conversion: 10 (or as many steps as desired; the more steps, the more finely fragmented it will be and the longer the simulation will take)

Expand pasture into forest nearest to existing agriculture:

focal landcover codes: 12

convertible landcover codes: 1 2 3 4 5

replacement landcover code: 10

check “Convert From Edge”

number of steps toward conversion: 1

Data needs

The only required input data to run the proximity-based scenario generator is a base land-use/land-cover map and user-defined land cover codes pertaining to this base map to designate how the scenarios should be computed.

1. Base land-use/cover map (required). This is the map that will be modified in the generation of the desired scenarios. All pixels in this map (that overlap with the area of interest, if included) other than the pixels that are converted will remain the same.

    Name: file can be named anything (scenario_proximity_lulc.tif in the sample data)

    Format: standard GIS raster file (e.g., ESRI GRID or IMG), with a column labeled ‘value’ that designates the LULC class code for each cell (integers only; e.g., 1 for forest, 10 for grassland, etc.)

1. AOI – Area of Interest (optional). If change is only desired in a subregion of the broader land-use/land-cover map, the user may designate this area of interest. Prior to scenario generation, the map will be clipped to the extent of this vector.

   Name: file can be named anything (scenario_proximity_aoi.shp in the sample data)

   Format: vector (polygon) file

2. Max area to convert (ha): enter the maximum numbers of hectares to be converted to agriculture. This is the maximum because due to the discretization of area of pixels, the number of pixels closest to but not exceeding this number will be converted.
3. Focal Landcover Codes: enter the LULC code(s) for the land cover types from which distance from edge should be calculated. If multiple values, they should be separated by spaces.
4. Convertible Landcover Codes: enter the LULC code(s) for the land cover types that are allowed to be converted to agriculture in the simulation. If multiple values, they should be separated by spaces.
5. Replacement Landcover Code: enter an integer that corresponds to the LULC code to which habitat will be converted. If there are multiple LULC types that are of interest for conversion, this tool should be run in sequence, choosing one type of conversion each time. A new code may be introduced if it is a novel land-use for the region or if it is desirable to track the expanded land-use as separate from historic land-use.
6. Check boxes: types of scenarios to generate
   1. Convert farthest from edge: land cover type(s) designated as “convertible” that are farthest from the edge of any land cover type designated as “focal” will be converted. Convertible land covers and habitat of interest land-covers may be the same, or a subset of one another, or they can be different. If they are the same, the number of steps for conversion should be specified, because the conversion of habitat within the focal land cover will create new habitat edge, resulting in a completely different pattern of conversion depending on how many steps are chosen.
   2. Convert nearest to edge: land cover type(s) designated as “convertible” that are nearest to the edge of any land cover type designated as “focal” will be converted. As for the previous scenario, convertible land covers and habitat of interest land-covers may be the same, or a subset of one another, or they can be different.
7. Number of Steps in Conversion: enter an integer for the number of steps the simulation should take to fragment the habitat of interest in the fragmentation scenario. Entering a 1 means that all of the habitat conversion will occur in the center of the patch of the habitat of interest. Entering 10 will be fragmented according to a pattern of sequentially converting the pixels furthest from the edge of that habitat, over the number of steps specified by the user.

Running the model

The model is available as a standalone application accessible from the install directory of InVEST (under the subdirectory invest-3_x86/invest_scenario_gen_proximity.bat).

Advanced Usage

This model supports avoided re-computation. This means the model will detect intermediate and final results from a previous run in the specified workspace and it will avoid re-calculating any outputs that are identical to the previous run. This can save significant processing time for successive runs when only some input parameters have changed.

Viewing Output from the Model

Upon successful completion of the model, a file explorer window will open to the output workspace specified in the model run. This directory contains an output folder holding files generated by this model. Those files can be viewed in any GIS tool such as ArcGIS, or QGIS. These files are described below in Section Interpreting Results.

Interpreting Results

Final Results

Final results are found in the *Workspace* folder within the specified for this module.

- **InVEST….log…txt**: Each time the model is run, a text (.txt) file will appear in the *Output* folder. The file will list the parameter values for that run and will be named according to the model, the date and time, and the suffix.
- **nearest_to_edge _<suffix>.tif:** LULC raster for the scenario of conversion nearest to the edge of the focal habitat
- **farthest_from_edge_<suffix>.tif:** LULC raster for the scenario of conversion farthest from the edge of the focal habitat
- **nearest_to__edge_<suffix>.csv:** table listing the area (in hectares) and number of pixels for different land cover types converted for the scenario of conversion nearest to the edge of the focal habitat
- **farthest_from_edge _<suffix>.csv:** table listing the area (in hectares) and number of pixels for different land cover types converted for the scenario of conversion nearest to the edge of the focal habitat

Intermediate Results

You may also want to examine the intermediate results. These files can help determine the reasons for the patterns in the final results. They are found in the *intermediate_outputs* folder within the*Workspace* specified for this module.

- **{farthest_from_/nearest_to}_edge_distance_<suffix>.tif:** map

  of This raster shows the distance (in number of pixels) of each pixel to the nearest edge of the focal landcover
- **_tmp_work_tokens:** This directory stores metadata used

  internally to enable avoided re-computation.

Sample Script

The following script is provided to demonstrate how the scenarios described in Section "How It Works" can be composed into a single script that's callable from the InVEST Python API.

import natcap.invest.scenario_generator_proximity_based

Habitat Quality

Summary

Biodiversity is intimately linked to the production of ecosystem services. Patterns in biodiversity are inherently spatial, and as such, can be estimated by analyzing maps of land use and land cover (LULC) in conjunction with threats to species' habitat. InVEST models habitat quality and rarity as proxies for biodiversity, ultimately estimating the extent of habitat and vegetation types across a landscape, and their state of degradation. Habitat quality and rarity are a function of four factors: each threat's relative impact, the relative sensitivity of each habitat type to each threat, the distance between habitats and sources of threats, and the degree to which the land is legally protected. The model assumes that the legal protection of land is effective and that all threats to a landscape are additive.

Introduction

A primary goal of conservation is the protection of biodiversity, including the range of genes, species, populations, habitats, and ecosystems in an area of interest. While some consider biodiversity to be an ecosystem service, here we treat it as an independent attribute of natural systems, with its own intrinsic value (we do not monetize biodiversity in this model). Natural resource managers, corporations and conservation organizations are becoming increasingly interested in understanding how and where biodiversity and ecosystem services align in space and how management actions affect both.

Evidence from many sources builds an overwhelming picture of pervasive biodiversity decline worldwide (e.g., Vitousek et al. 1997; Wilcove et al 1998; Czech et. al 2000). This evidence has prompted a wide-ranging response from both governments and civil society. Through the Rio Convention on Biodiversity, 189 nations have committed themselves to preserving the biodiversity within their borders. Yet, there is scant research on the overlap between opportunities to protect biodiversity and to sustain the ecosystem services so critical to these countries' economic well-being. This is precisely the type of challenge that InVEST has been designed to address.

For managers to understand the patterns of distribution and richness across a landscape, individually and in aggregate, it is necessary to map the range or occurrences of elements (e.g. species, communities, habitats). The degree to which current land use and management affects the persistence of these elements must also be assessed in order to design appropriate conservation strategies and encourage resource management that maximizes biodiversity in those areas.

There are a variety of approaches to identifying priorities for conservation with various trade-offs among them. Each of these approaches focuses on different facets of biodiversity attributes and dynamics, including habitat or vegetation-based representation (i.e., a coarse filter), maximizing the number of species "covered" by a network of conserved sites for a given conservation budget (Ando et al. 1998), identifying patterns of richness and endemism (Conservation International hotspots), and conserving ecological processes. There is also a hybrid coarse-fine filter approach which selectively includes "fine-filter" elements such as species with unique habitat requirements who may not be adequately protected using a coarse-filter approach only (The Nature Conservancy and World Wildlife Fund ecoregional planning). The InVEST Habitat Quality model is most relevant to "coarse filter", or habitat-based approaches.

The reasons for modeling biodiversity alongside ecosystem services are simple and powerful. Doing so allows us to compare spatial patterns of biodiversity and ecosystem services, and to identify win-win areas (i.e., areas where conservation can benefit both natural systems and human economies) as well as areas where these goals are not aligned. Further, it allows us to analyze trade-offs between biodiversity and ecosystem services across differing scenarios of future land use change. Land use/land cover (LULC) patterns that generate greater ecosystem service production may not always lead to greater biodiversity conservation (Nelson et al. 2008), and modeling future options today can help identify and avoid tradeoffs.

The Model

The InVEST Habitat Quality model combines information on LULC and threats to biodiversity to produce habitat quality maps. This approach generates two key sets of information that are useful in making an initial assessment of conservation needs: the relative extent and degradation of different types of habitat types in a region, and changes across time. This approach further allows rapid assessment of the status of and change in habitat as a proxy for more detailed measures of biodiversity status. If habitat changes are taken as representative of genetic, species, or ecosystem changes, the user is assuming that areas with high quality habitat will better support all levels of biodiversity and that decreases in habitat extent and quality over time means a decline in biodiversity persistence, resilience, breadth and depth in the area of decline.

The habitat rarity portion of the model indicates the extent and pattern of natural land cover types on the current or a potential future landscape vis-a-vis the extent of the same natural land cover types in some baseline period. Rarity maps allow users to create a map of the rarest habitats on the landscape relative to the baseline chosen by the user to represent the mix of habitats on the landscape that is most appropriate for the study area's native biodiversity.

The model requires basic data that are available virtually everywhere in the world, making it useful in areas for which species distribution data are poor or lacking altogether. Extensive occurrence (presence/absence) data may be available in many places for current conditions. However, modeling the change in occurrence, persistence, or vulnerability of multiple species under future conditions is often impossible or infeasible. While a habitat approach leaves out the detailed species occurrence data available for current conditions, several of its components represent advances in functionality over many existing biodiversity conservation planning tools. The most significant is the ability to characterize the sensitivity of habitat types to various threats. Not all habitats are affected by all threats in the same way, and the InVEST model accounts for this variability. Further, the model allows users to estimate the relative impact of one threat over another so that threats that are more damaging to biodiversity persistence on the landscape can be represented as such. For example, grassland could be particularly sensitive to threats generated by urban areas yet moderately sensitive to threats generated by roads. In addition, the distance over which a threat will degrade natural systems is incorporated into the model.

Model assessment of the current landscape can be used as an input to a coarse-filter assessment of current conservation needs and opportunities. Model assessment of potential LULC futures can be used to measure potential changes in habitat extent, quality, and rarity on a landscape and conservation needs and opportunities in the future.

How it Works

Habitat Quality

We define habitat as "the resources and conditions present in an area that produce occupancy – including survival and reproduction – by a given organism" (Hall et al. 1997:175). Habitat quality refers to the ability of the ecosystem to provide conditions appropriate for individual and population persistence, and is considered a continuous variable in the model, ranging from low to medium to high, based on resources available for survival, reproduction, and population persistence, respectively (Hall et al 1997). Habitat with high quality is relatively intact and has the structure and function within the range of historic variability. Habitat quality depends on a habitat's proximity to human land uses and the intensity of these land uses. Generally, habitat quality is degraded as the intensity of nearby land-use increases (Nelleman 2001, McKinney 2002, Forman et al. 2003).

The model runs using raster data, where each cell in the raster is assigned an LULC class, which can be a natural (unmanaged) class or a managed class. LULC types can be given at any level of classification detail. For example, grassland is a broad LULC definition that can be subdivided into pasture, restored prairie, and residential lawn types to provide much more habitat classification detail. While the user can submit up to 3 raster maps of LULC, one each for a baseline, current, and future period, at a minimum the current LULC raster map must be provided.

The user defines which LULC types can provide habitat for the conservation objective (e.g., if forest breeding birds are the conservation objective then forests are habitat and non-forest covers are not habitat).
Let H_jHj indicate the habitat suitability of LULC type jj.
Which LULC types should be considered habitat? If considering biodiversity generally or if data on specific biodiversity-habitat relationships are lacking, you can take a simple binary approach to assigning habitat to LULC types. A classic example would be to follow an island-ocean model and assume that the managed land matrix surrounding remnant patches of unmanaged land is unusable from the standpoint of species (e.g., MacArthur and Wilson 1967). In this case a 0 would be assigned to managed LULC types in the matrix (i.e., non-habitat) and a 1 to unmanaged types (i.e., habitat). Under this modeling scheme habitat quality scores are not a function of habitat importance, rarity, or suitability; all habitat types are treated equally. Model inputs are assumed to not be specific to any particular species or species guild, but rather apply to biodiversity generally.

More recent research suggests that the matrix of managed land that surrounds patches of unmanaged land can significantly influence the "effective isolation" of habitat patches, rendering them more or less isolated than simple distance or classic models would indicate (Ricketts 2001, Prugh et al. 2008). Modification of the matrix may provide opportunities for reducing patch isolation and thus the extinction risk of populations in fragmented landscapes (Franklin and Lindenmayer 2009). To model this, a relative habitat suitability score can be assigned to an LULC type ranging from 0 to 1 where 1 indicates the highest habitat suitability. A ranking of less than 1 indicates habitat where a species or functional group may have lower survivability. Applying this second approach greatly expands the definition of habitat from the simple and often artificial binary approach (e.g., "natural" versus "unnatural") to include a broad spectrum of both managed and unmanaged LULC types. By using a continuum of habitat suitability across LULC types, the user can assess the importance of land use management on habitat quality holistically or consider the potential importance of "working" (or managed) landscapes.

If a continuum of habitat suitability is relevant, weights with a roster of LULC on a landscape must be applied in reference to a particular species guild of group. For example, grassland songbirds may prefer a native prairie habitat above all other habitat types (the habitat score for the LULC prairie (H_{prarie} equals 1), but will also make use of a managed hayfield or pasture if prairie is not available (the habitat score for the LULC hayfield ($H_{hayfield}$) and pasture ($H_{pasture}$) equals 0.5). However, mammals such as porcupines will find prairie unsuitable for breeding and feeding. Therefore, if specific data on species group-habitat relationships are used, the model output refers to habitat extent and quality for the species or group in the modeled set only. Besides a map of LULC and data that relates LULC to habitat suitability, the model also requires data on habitat threat density and its effects on habitat quality. In general, we consider threats to be human-modified LULC types that cause habitat fragmentation, edge, and degradation in neighboring habitat. For example, the conversion of a habitat LULC to non-habitat LULC reduces the size and continuity of neighboring habitat patches. Edge effects refer to changes in the biological and physical conditions that occur at a patch boundary and within adjacent patches. For example, adjacent degraded non-habitat LULC parcels impose "edge effects" on habitat parcels and can have negative impacts within habitat parcels by, for example, facilitating entry of predators, competitors, invasive species, or toxic chemicals and other pollutants. Another example: in many developing countries roads are a threat to forest habitat quality on the landscape because of the access they provide to timber and non-timber forest harvesters.

Each threat source needs to be mapped on a raster grid. A grid cell value on a threat's map can either indicate intensity of the threat within the cell (e.g., road length in a grid cell or cultivated area in a gird cell) or simply a 1 if the grid cell contains the threat in a road or crop field cover and 0 otherwise. Let o_{ry} indicate threat r's "score" in grid cell y where r = 1, 2, …, R indexes all modeled degradation sources.
All mapped threats should be measured in the same scale and metric. For example, if one threat is measured in density per grid cell then all degradation sources should be measured in density per grid cell where density is measured with the same metric unit (e.g., km and km^2). Or if one threat is measured with presence/absence (1/0) on its map then all threats should be mapped with the presence/absence scale.

The impact of threats on habitat in a grid cell is mediated by four factors.

1. The first factor is **the relative impact of each threat**. Some threats may be more damaging to habitat, all else equal, and a relative impact score accounts for this (see Table 1 for a list of possible threats). For instance, urban areas may be considered to be twice as degrading to any nearby habitats as agricultural areas. A degradation source's weight, w_r, indicates the relative destructiveness of a degradation source to all habitats. The weight w_r can take on any value from 0 to 1. For example, if urban area has a threat weight of 1 and the threat weight of roads is set equal to 0.5 then the urban area causes twice the disturbance, all else equal, to all habitat types. To reiterate, if we have assigned species group-specific habitat suitability scores to each LULC then the threats and their weights should be specific to the modeled species group.
2. The second mitigating factor is **the distance between habitat and the threat source and the impact of the threat across space**. In general, the impact of a threat on habitat decreases as distance from the degradation source increases, so that grid cells that are more proximate to threats will experience higher impacts. For example, assume a grid cell is 2 km from the edge of an urban area and 0.5 km from a highway. The impact of these two threat sources on habitat in the grid cell will partly depend on how quickly they decrease, or decay, over space. The user can choose either a linear or exponential distance-decay function to describe how a threat decays over space. The impact of threat r that originates in grid cell y, r_y, on habitat in grid cell x is given by i_{rxy} and is represented by the following equations:

(1)

$$i_{rxy}=1-(d_{xy}/d_{r\ max})\ \text{if linear}$$

(2)

$$i_{rxy}=\exp\left(-\left(2.99/d_{r\ max}\right)d_{xy}\right) \text{if exponential}$$

where d_{xy} is the linear distance between grid cells x and y and $d_{r\ max}$ is the maximum effective distance of threat r's reach across space. Figure 1 illustrates the relationship between the distance-decay rate for a threat based on the maximum effective distance of the threat (linear and exponential). For example, if the user selects an exponential decline and the maximum impact distance of a threat is set at 1 km, the impact of the threat on a grid cell's habitat will decline by ~ 50% when the grid cell is 200 m from r's source. If $i_{rxy}>0$ then grid cell x is in degradation source r_y's disturbance zone. (If the exponential function is used to describe the impact of degradation source r on the landscape then the model ignores values of i_{rxy} that are very close to 0 in order to expedite the modeling process.) To reiterate, if we have assigned species group-specific habitat suitability scores to each LULC then threat impact over space should be specific to the modeled species group.

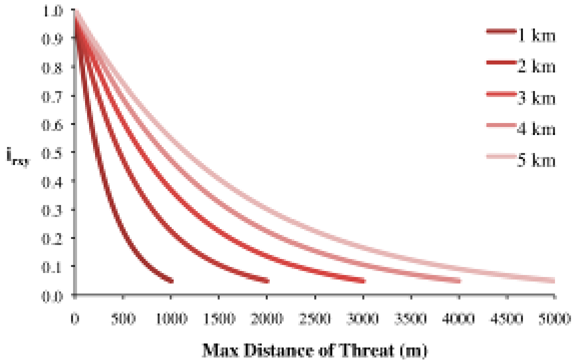

Figure 1. An example of the relationship between the distance-decay rate of a threat and the maximum effective distance of a threat.

3. The third landscape factor that may mitigate the impact of threats on habitat is **the level of legal / institutional / social / physical protection from disturbance in each cell**. Is the grid cell in a formal protected area? Or is it inaccessible to people due to high elevations? Or is the grid cell open to harvest and other forms of disturbance? The model assumes that the more legal / institutional / social / physical protection from degradation a cell has, the less it will be affected by nearby threats, no matter the type of threat. Let $\beta_x \in [0,1]$ indicate the level of accessibility in grid cell x where 1 indicates complete accessibility. As accessibility decreases the impact that all threats will have in grid cell x decreases linearly. It is important to note that while legal / institutional / social / physical protections often do diminish the impact of extractive activities in habitat such as hunting or fishing, it is unlikely to protect against other sources of degradation such as air or water pollution, habitat fragmentation, or edge effects. If the threats considered are not mitigated by legal / institutional / social / physical properties then you should ignore this input or set $\beta_x=1$ for all grid cells x. To reiterate, if we have assigned species group-specific habitat suitability scores to each LULC then the threats mitigation weights should be specific to the modeled species group.
4. The **relative sensitivity of each habitat type to each threat on the landscape** is the final factor used when generating the total degradation in a cell with habitat. (In Kareiva et al. (2010), habitat sensitivity is referred to by its inverse, "resistance".) Let $S_{jr} \in [0,1]$ indicate the sensitivity of LULC (habitat type) j to threat r where values closer to 1 indicate greater sensitivity. The model assumes that the more sensitive a habitat type is to a threat, the more degraded the habitat type will be by that threat. A habitat's sensitivity to threats should be based on general principles from landscape ecology for conserving biodiversity (e.g., Forman 1995; Noss 1997; Lindenmayer et al 2008). To reiterate, if we have assigned species group-specific habitat suitability scores to each LULC then habitat sensitivity to threats should be specific to the modeled species group.

Therefore, the total threat level in grid cell x with LULC or habitat type j is given by D_{xj},

(3)

$$D_{xj}=\sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(w_r\Big/\sum_{r=1}^{R}w_r\right)r_y i_{rxy}\beta_x S_{jr}$$

where yy indexes all grid cells on rr's raster map and Y_rYr indicates the set of grid cells on rr's raster map. Note that each threat map can have a unique number of grid cells due to variation in raster resolution.

If $S_{jr}=0$Sjr=0 then D_{xj}Dxj is not a function of threat rr. Also note that threat weights are normalized so that the sum across all threats weights equals 1.

By normalizing weights such that they sum to 1 we can think of D_{xj}Dxj as the weighted average of all threat levels in grid cell xx. The map of D_{xj}Dxj will change as the set of weights we use change. Please note that two sets of weights will only differ if the relative differences between the weights in each set differ. For example, set of weights of 0.1, 0.1, and 0.4 are the same as the set of weights 0.2, 0.2, and 0.8.

A grid cell's degradation score is translated into a habitat quality value using a half saturation function where the user must determine the half-saturation value. As a grid cell's degradation score increases its habitat quality decreases. Let the quality of habitat in parcel xx that is in LULC jj be given by Q_{xj}Qxj where,

(4)

$$Q_{xj}=H_j(1-(D_{zxj}/D_{zxj}+k_z))$$

and z (we hard code $z=2.5$z=2.5) and k are scaling parameters (or constants). Q_{xj} is equal to 0 if H_j = 0 . Q_{xj} increases in H_j and decreases in D_{xj}. Q_{xj} can never be greater than 1. The k constant is the half-saturation constant and is set by the user. The parameter k is equal to the D value where $1-(D_{zxj}/D_{zxj}+k_z=0.5)$. For example, if k=then $1-(D_{zxj}/D_{zxj}+k_z)=0.5$ when $D_{xj}=5$Dxj=5. By default, you can set $k=0.5$ (see note in Data Needs section). If you are doing scenario analyses, whatever value you chose for k for the first landscape you ran the model on, that same k must be used for all alternative scenarios on the same landscape. Similarly, whatever spatial resolution you chose the first time you ran the model on a landscape use the same value for all additional model runs on the same landscape. If you want to change your choice of k or the spatial resolution for any model run then you have to change the parameters for all model runs, if you are comparing multiple scenarios on the same landscape.

Threat	Number of species endangered by threat, as indicated by Lowe et al. (1990), Moseley (1992), and Beacham (1994)	Estimated number of species endangered by threat, derived by extrapolation of 5% sample from *Federal Register*
Interactions with non-native species	305	340
Urbanization	275	340
Agriculture	224	260
Outdoor recreation and tourism development	186	200
Domestic livestock and ranching activities	182	140
Reservoirs and other running water diversions	161	240
Modified fire regimes and silviculture	144	80
Pollution of water, air, or soil	144	140
Mineral, gas, oil, and geothermal extraction or exploration	140	140
Industrial, institutional, and military activities	131	220
Harvest, Intentional and incidental	120	220
Logging	109	80
Road presence, construction, and maintenance	94	100
Loss of genetic variability, inbreeding depression, or hybridization	92	240
Aquifer depletion, wetland draining or filling	77	40
Native species interactions, plant succession	77	160
Disease	19	20
Vandalism (destruction without harvest)	12	0

Table 1. Possible degradation sources based on the causes of endangerment for American species classified as threatened or endangered by the US Fish and Wildlife Service. Adapted from Czech et al. 2000.

Habitat Rarity

While mapping habitat quality can help to identify areas where biodiversity is likely to be most intact or imperiled, it is also critical to evaluate the relative rarity of habitats on the landscape regardless of quality. In many conservation plans, habitats that are rarer are given higher priority, simply because options and opportunities for conserving them are limited and if all such habitats are lost, so too are the species and processes associated with them.

The relative rarity of an LULC type on a current or projected landscape is evaluated vis-a-vis a baseline LULC pattern. A rare LULC type on a current or projected map that is also rare on some ideal or reference state on the landscape (the baseline) is not likely to be in critical danger of disappearance, whereas a rare LULC type on a current or projected map that was abundant in the past (baseline) is at risk.

In the first step of the rarity calculation we take the ratio between the current or projected and past (baseline) extents of each LULC type jj. Subtracting this ratio from one, the model derives an index that represents the rarity of that LULC class on the landscape of interest.

(5)

$$R_j=1-N_j/N_{j_{baseline}}$$

where N_j is the number of grid cells of LULC j on the current or projected map and $N_{j_{baseline}}$ gives the number of grid cells of LULC j on the baseline landscape. The calculation of R_j requires that the baseline, current, and/or projected LULC maps are all in the same resolution. In this scoring system, the closer to 1 a LULC's RR score is, the greater the likelihood that the preservation of that LULC type on the current or future landscape is important to biodiversity conservation. If LULC j did not appear on the baseline landscape then we set $R_j=0$.

Once we have a R_j measure for each LULC type, we can quantify the overall rarity of habitat type in grid cell xx with:

(6)

$$R_x=\sum_{x=1}^{X}\sigma_{xj}R_j$$

where $\sigma_{xj}=1$σxj=1 if grid cell x is in LULC j on a current or projected landscape and equals 0 otherwise.

Limitations and Simplifications

In this model all threats on the landscape are additive, although there is evidence that, in some cases, the collective impact of multiple threats is much greater than the sum of individual threat levels would suggest.

Because the chosen landscape of interest is typically nested within a larger landscape, it is important to recognize that a landscape has an artificial boundary where the habitat threats immediately outside of the study boundary have been clipped and ignored. Consequently, threat intensity will always be less on the edges of a given landscape. There are two ways to avoid this problem. One, you can choose a landscape for modeling purposes whose spatial extent is significantly beyond the boundaries of your landscape of interest. Then, after results have been generated, you can extract the results just for the interior landscape of interest. Or you can limit your analysis to landscapes where degradation sources are concentrated in the middle of the landscape.

Data Needs

This section outlines the specific data used by the model. Please consult the InVEST sample data (located in the folder where InVEST is installed, if you also chose to install sample data) for examples of all of these data inputs. This will help with file type, folder structure and table formatting - this is particularly important for Habitat Quality, as its requirements for file and folder structure and naming are more complex than some other InVEST models. Note that all GIS inputs must be in the same projected coordinate system and in linear meter units.

- **Workspace** (required). Folder where model outputs will be written. Make sure that there is ample disk space, and write permissions are correct.
- **Results suffix** (optional). Text string that will be appended to the end of output file names, as "_Suffix". Use a Suffix to differentiate model runs, for example by providing a short name for each scenario. If a Suffix is not provided, or is not changed between model runs, the tool will overwrite previous results.
- **Current Land Cover** (required). A GIS raster dataset, with an integer LULC code for each cell. The LULC raster should include the area of interest, as well as a buffer of the width of the greatest maximum threat distance. Otherwise, locations near the edge of the area of interest may have inflated habitat quality scores, because threats outside the area of interested are not properly accounted for. *The LULC codes must match the codes in the "Sensitivity of land cover types to each threat" table below.*
- **Future Land Cover** (optional). A GIS raster dataset that represents a future projection of LULC in the landscape with an integer LULC code for each cell. This file should be formatted exactly like the "Current Land Cover" above. LULC classes that appear on both the current and future maps should have the same LULC code. LULC types unique to the future map should have codes not used in the current LULC map. Again, the LULC raster should include the area of interest, as well as a buffer of the width of the greatest

maximum threat distance. Otherwise, locations near the edge of the area of interest may have inflated habitat quality scores, because threats outside the area of interested are not properly accounted for.

- **Baseline Land Cover** (optional). A GIS raster dataset of LULC types on a baseline landscape with an integer LULC code for each cell. This file should be formatted exactly like the "Current Land Cover" above. The LULC types that are common to the current or future and baseline landscapes should have the same LULC code across all maps. LULC types unique to the baseline map should have codes not used in the current or future LULC map. Again, the LULC raster should include the area of interest, as well as a buffer of the width of the greatest maximum threat distance. Otherwise, locations near the edge of the area of interest may have inflated habitat quality scores, because threats outside the area of interested are not properly accounted for. Used to calculate habitat rarity.

  If possible, the baseline map should refer to a time when intensive management of the land was relatively rare. For example, a map of LULC in 1851 in the Willamette Valley of Oregon, USA, captures the LULC pattern on the landscape before it was severely modified by massive agricultural production. Granted, this landscape had been modified by American Indian land clearing practices such as controlled fires as well.

- **Folder Containing Threat Rasters** (required). Folder containing GIS raster files of the distribution and intensity of each individual threat, with values between 0 and 1. You will have as many of these maps as you have threats. These threat maps should cover the area of interest, as well as a buffer of the width of the greatest maximum threat distance. Otherwise, locations near the edge of the area of interest may have inflated habitat quality scores, because threats outside the area of interested are not properly accounted for.

  Each cell in the raster contains a value that indicates the density or presence of a threat within it (e.g., area of agriculture, length of roads, or simply a 1 if the grid cell is a road or crop field and 0 otherwise). All threats should be measured in the same scale and units (i.e., all measured in density terms or all measured in presence/absence terms) and not some combination of metrics. The extent and resolution of these raster datasets does not need to be identical to that of the input LULC maps. In cases where the threats and LULC map resolutions vary, the model will use the resolution and extent of the LULC map. Do not leave any area on the threat maps as 'No Data'. If pixels do not contain that threat set the pixels' threat level equal to 0.

  InVEST will not prompt you for these rasters in the tool interface. It will instead automatically find each one in the user-specified Folder, based on names in the **Threats data** table.

  Raster naming requirements: The name of each raster file must exactly match the name of a degradation source in the rows of the Threats data table. File names cannot be longer than 7 characters if using ESRI GRID format (so TIFFs are recommended.) If you are analyzing habitat quality for more than one LULC scenario (e.g., a current and future map or a baseline, current, and future map) then you need a set of threat layers for each modeled scenario. Add "_c" at the end of the raster name for all "current" threat layers, "_f" for all future threat layers, and "_b" for all "baseline" threat layers. For example, a raster corresponding to a THREAT of agriculture (called "Agric" in the Threats data table below) in the current scenario should be named "Agric_c.tif", named "Agric_f.tif" in the future scenario and "Agric_b.tif" in the baseline scenario. If you do not use such endings then the model assumes the degradation source layers correspond to the current map. If a threat noted in the Threats data table is inappropriate for the LULC scenario that you are analyzing (e.g., industrial development on a Willamette Valley pre-settlement map from 1851) then enter a threat map for that time period that has all 0 values. If you do not include threat maps for an input LULC scenario then the model will not calculate habitat quality on the scenario LULC map.

  Finally, note that we assume that the relative weights of threats and sensitivity of habitat to threats do not change over time, so we only submit one Threat data table and one Habitat sensitivity data table. If you want to change these over time then you will have to run the model multiple times.

  In the sample datasets, threat rasters are called the following: crp_c; crp_f; rr_c; rr_f; urb_c; urb_f; rot_c; rot_f; prds_c; prds_f; srds_c; srds_f; lrds_c; lrds_f. By using these sets of inputs we are running a habitat quality analysis for the current (_c) and future (_f) LULC scenario maps. A habitat quality map will not be generated for the baseline map because we have not provided any threat layers for the baseline map. The name 'crp' refers to cropland, 'rr' to rural residential, 'urb' to urban, 'rot' to rotation forestry, 'prds' to primary roads, 'srds' to secondary roads, and 'lrds' to light roads.

- **Threats data** (required). A CSV (comma-separated value, .csv) table of all threats you want the model to consider. The table contains information on the each threat's relative importance or weight and its impact across space.

  Each row in the Threats data CSV table is a degradation source, and columns must be named as follows:

- *THREAT*. The name of the specific threat. **Threat names must not exceed 8 characters.**
- *MAX_DIST*. The maximum distance over which each threat affects habitat quality (measured in kilometers). The impact of each degradation source will decline to zero at this maximum distance.
- *WEIGHT*. The impact of each threat on habitat quality, relative to other threats. Weights can range from 1 at the highest impact, to 0 at the lowest.
- *DECAY*. The type of decay over space for the threat. Can have the value of either "linear" or "exponential".

Example: Hypothetical study with three threats. Agriculture (*Agric* in the table) degrades habitat over a larger distance than roads do, and has a greater overall magnitude of impact. Further, paved roads (*Paved_rd*) attract more traffic than dirt roads (*Dirt_rd*) and thus are more destructive to nearby habitat than dirt roads.

THREAT	MAX_DIST	WEIGHT	DECAY
Dirt_rd	2	0.1	Linear
Paved_rd	4	0.4	exponential
Agric	8	1	Linear

- **Accessibility to Threats** (optional): A GIS polygon shapefile containing data on the relative protection that legal / institutional / social / physical barriers provide against threats. Polygons with minimum accessibility (e.g., strict nature reserves, well protected private lands) are assigned some number less than 1, while polygons with maximum accessibility (e.g., extractive reserves) are assigned a value 1. These polygons can be land management units or a regular array or hexagons or grid squares. Any cells not covered by a polygon will be assumed to be fully accessible and assigned values of 1.

  In the shapefile's attribute table, each row is a specific polygon on the landscape, and columns must be named as follows:

  - *ID*: Unique identifying integer code for each polygon.
  - *ACCESS*: Values between 0 and 1 for each polygon, as described above.
- **Sensitivity of Land Cover Types to Each Threat** (required): A CSV (comma-separated value, .csv) table of LULC types, whether or not they are considered habitat, and, for LULC types that are habitat, their specific sensitivity to each threat.

  Each row in the Sensitivity CSV table is an LULC type, and columns must be named as follows:

  - *LULC*: Numeric integer code for each LULC type. Values must match the codes used in the current, future and baseline LULC rasters. *All LULC types that appear in the current, future, or baseline maps must have a row in this table.*
  - *NAME*: The name of each LULC
  - *HABITAT*: Each LULC type is assigned a habitat score (H_jHj in the equations above), from 0 to 1. If you want to simply classify each LULC as habitat or not without reference to any particular species group then use 0s and 1s where a 1 indicates habitat. Otherwise, if sufficient information is available on a species group's habitat preferences, assign the LULC a relative habitat suitability score between 0 and 1 where 1 indicates the highest habitat suitability. For example, a grassland songbird may prefer a native prairie habitat above all other habitat types (prairie is given a "HABITAT" score of 1 for grassland birds), but will also use a managed hayfield or pasture if prairie is not available (managed hayfield and pasture are given a "HABITAT" score of 0.5 for grassland birds).
  - *L_THREAT1, L_THREAT2*, etc.: The relative sensitivity of each habitat type to each threat. You will have as many columns named like this as you have threats, and the "_THREAT1", "_THREAT2" etc portions of the column names must match row names in the "Threat data" table noted above. Values range from 0 to 1, where 1 represents high sensitivity to a threat and 0 represents no sensitivity. Note: Even if the LULC is not considered habitat, do not leave its sensitivity to each threat as Null or blank, instead enter a 0 and the model will convert it to NoData.

  Example: A hypothetical study with four LULC types and three threats. In this example we treat Closed Woodland and Forst Mosaic as (absolute) habitat and Bare Soil and Cultivation as (absolute) non-habitat. Forest mosaic is the most sensitive (least resistant) habitat type, and is more sensitive to dirt roads

(L_DIRT_RD, value 0.9) than paved roads (L_PAVED_RD, value 0.5) or agriculture (L_AGRIC value 0.8). We enter 0s across all threats for the two developed land covers, Bare Soil and Cultivation, since they are not habitat.

LULC	NAME	HABITAT	L_AGRIC	L_PAVED_RD	L_DIRT_RD
1	Bare Soil	0	0	0	0
2	Closed Woodland	1	0.5	0.2	0.4
3	Cultivation	0	0	0	0
4	Forest Mosaic	1	0.8	0.8	0.5

- **Half-saturation constant** (required): This is the value of the parameter k in equation (4). By default it is set to 0.5 but can be set equal to any positive floating point number. In general, you want to set k to half of the highest grid cell degradation value on the landscape. To perform this model calibration you will have to the run the model once to find the highest degradation value and set k for your landscape. For example, if a preliminary run of the model generates a degradation map where the highest grid-cell degradation level is 1 then setting k at 0.5 will produce habitat quality maps with the greatest variation on the 0 to 1 scale (this helps with visual representation of heterogeneity in quality across the landscape). It is important to note that the rank order of grid cells on the habitat quality metric is invariant to your choice of k. The choice of k only determines the spread and central tendency of habitat quality scores. It is important to use the same value of k for all runs that involve the same landscape. If you want to change your choice of k for any model run then you must change the parameters for all model runs.

Running the Model

To launch the Habitat Quality model navigate to the Windows Start Menu -> All Programs -> InVEST [*version*] -> Habitat Quality. The interface does not require a GIS desktop, although the results will need to be explored with any GIS tool such as ArcGIS or QGIS.

Interpreting Results

The following is a short description of each of the outputs from the Habitat Quality model. Final results are found within the user defined Workspace specified for this model run. “Suffix” in the following file names refers to the optional user-defined Suffix input to the model.

- **[Workspace]** folder:
  - **Parameter log**: Each time the model is run, a text (.txt) file will be created in the Workspace. The file will list the parameter values and output messages for that run and will be named according to the service, the date and time. When contacting NatCap about errors in a model run, please include the parameter log.
- **[Workspace]\output** folder:
  - **deg_sum_out_c_[Suffix].tif** – Relative level of habitat degradation on the current landscape. A high score in a grid cell means habitat degradation in the cell is high relative to other cells. Grid cells with non-habitat land cover (LULC with H_j = 0) get a degradation score of 0. This is a mapping of degradation scores calculated with equation (3).
  - **deg_sum_out_f_[Suffix].tif** – Relative level of habitat degradation on the future landscape. A high score in a grid cell means habitat degradation in the cell is high relative to other cells. This output is only created if a future LULC map is given as input. Grid cells with non-habitat land cover (LULC with H_j = 0) get a degradation score of 0. This is a mapping of degradation scores calculated with equation (3).
  - **quality_out_c_[Suffix].tif** – Relative level of habitat quality on the current landscape. Higher numbers indicate better habitat quality vis-a-vis the distribution of habitat quality across the rest of the

landscape. Areas on the landscape that are not habitat get a quality score of 0. This quality score is unitless and does not refer to any particular biodiversity measure. This is a mapping of habitat qulaity scores calculated with equation (4).

- **quality_out_f_[Suffix].tif** – Relative level of habitat quality on the future landscape. Higher numbers indicate better habitat quality vis-a-vis the distribution of habitat quality across the rest of the landscape. This output is only created if a future LULC map is given as input. Areas on the landscape that are not habitat get a quality score of 0. This quality score is unitless and does not refer to any particular biodiversity measure. This is a mapping of habitat qulaity scores calculated with equation (4).
- **rarity_c_[Suffix].tif** – Relative habitat rarity on the current landscape vis-a-vis the baseline map. This output is only created if a baseline LULC map is given as input. This map gives each grid cell's value of R_x (see equation (6)). The rarer the habitat type in a grid cell is vis-a-vis its abundance on the baseline landscape, the higher the grid cell's value in rarity_c.tif.
- **rarity_f_[Suffix].tif** – Relative habitat rarity on the future landscape vis-a-vis the baseline map. This output is only created if both baseline and future LULC maps are given as input. This map gives each grid cell's value of R_x (see equation (6)). The rarer the habitat type in a grid cell is vis-a-vis its abundance on the baseline landscape, the higher the grid cell's value in rarity_f.tif.

- **[Workspace]\intermediate** folder:

  This folder contains some of the intermediate files created during the model run. Usually you do not need to work with these files, unless you are trying to better understand how the model works, or debugging a model run. They include maps of habitats (**habitat__[b,c,f].tif**), threats layers processed with Threats data table attributes (**[threat]_filtered_[b,c,f].tif**), sensitivity applied to different threats (**sens_[threat]_[b,c,f].tif**), and a rasterized version of the Access input (**access_layer.tif**).

Modifying Output and Creating a Landscape Biodiversity Score

The model output does not provide landscape-level quality and rarity scores for comparing the baseline, current, and future LULC scenarios. Instead the user must summarize habitat extent and quality and rarity scores for each landscape. At the simplest level, a habitat quality landscape score for an LULC scenario is simply the aggregate of all grid cell-level scores under the scenario. In other words, we can sum all grid-level quality scores from the *quality_out_c.tif*, *quality_out_b.tif* (if available), and *quality_out_f.tif* (if available) maps and then compare scores. A map may have a higher aggregate quality score for several reasons. For one, it may just have more habitat area. However, if the amount of habitat across any two scenarios is approximately the same then a higher landscape quality score is indicative of better overall quality habitat.

Scores for certain areas on a landscape could also be compared. For example, we could compare aggregate habitat quality scores in areas of the landscape that are known to be in the geographic ranges of species of interest. For example, suppose we have geographic range maps of 9 species and have provided current and future LULC scenario maps to the Habitat Quality model. In this case we would determine 18 aggregate habitat quality scores, once for each modeled species under each scenario (current and future). Let G_{scur}Gscur indicate the set of grid cells on the current landscape that are in ss' range. Then the average habitat quality score in species ss' range on the current landscape is given by,

(7)

$$Q_{Scur}=\sum_{x=1}^{G_{scur}} Q_{xjcur}/G_{Scur}$$

where Q_{xjcur} indicates the habitat quality score on pixel xx in LULC j on the current landscape and $Q_{xjcur}=0$ if quality_out.tif for pixel xx is "No Data". The average range-normalized habitat quality score for all 9 species on the current landscape would be given by,

(8)

$$R_x=\sum_{x=1}^{X} \sigma_{xj} R_j$$

Then we would repeat for the future landscape with the grid cells in set G_{sfut}Gsfut for each species ss and the set of Q_{xjfut}Qxjfut.

Annual Water Yield

Summary

Hydropower accounts for twenty percent of worldwide energy production, most of which is generated by reservoir systems. InVEST estimates the annual average quantity and value of hydropower produced by reservoirs, and identifies how much water yield or value each part of the landscape contributes annually to hydropower production. The model has three components: water yield, water consumption, and hydropower valuation. The biophysical models do not consider surface – ground water interactions or the temporal dimension of water supply. The valuation model assumes that energy pricing is static over time.

Introduction

The provision of fresh water is an ecosystem service that contributes to the welfare of society in many ways, including through the production of hydropower, the most widely used form of renewable energy in the world. Most hydropower production comes from watershed-fed reservoir systems that generally deliver energy consistently and predictably. The systems are designed to account for annual variability in water volume, given the likely levels for a given watershed, but are vulnerable to extreme variation caused by land use and land cover (LULC) changes. LULC changes can alter hydrologic cycles, affecting patterns of evapotranspiration, infiltration and water retention, and changing the timing and volume of water that is available for hydropower production (World Commission on Dams 2000; Ennaanay 2006).

Changes in the landscape that affect annual average water yield upstream of hydropower facilities can increase or decrease hydropower production capacity. Maps of where water yield used for hydropower is produced can help avoid unintended impacts on hydropower production or help direct land use decisions that wish to maintain power production, while balancing other uses such as conservation or agriculture. Such maps can also be used to inform investments in restoration or management that downstream stakeholders, such as hydropower companies, make in hopes of improving or maintaining water yield for this important ecosystem service. In large watersheds with multiple reservoirs for hydropower production, areas upstream of power plants that sell to a higher value market will have a higher value for this service. Maps of how much value each parcel contributes to hydropower production can help managers avoid developments in the highest hydropower value areas, understand how much value will be lost or gained as a consequence of different management options, or identify which hydropower producers have the largest stake in maintaining water yield across a landscape.

The Model

The InVEST Water Yield model estimates the relative contributions of water from different parts of a landscape, offering insight into how changes in land use patterns affect annual surface water yield and hydropower production.

Modeling the connections between landscape changes and hydrologic processes is not simple. Sophisticated models of these connections and associated processes (such as the WEAP model) are resource and data intensive and require substantial expertise. To accommodate more contexts, for which data are readily available, InVEST maps and models the annual average water yield from a landscape used for hydropower production, rather than directly addressing the effect of LULC changes on hydropower, as this process is closely linked to variation in water inflow on a daily to monthly timescale. Instead, InVEST calculates the relative contribution of each land parcel to annual average hydropower production and the value of this contribution in terms of energy production. The net present value of hydropower production over the life of the reservoir also can be calculated by summing discounted annual revenues.

How it Works

The model runs on a gridded map. It estimates the quantity and value of water used for hydropower production from each subwatershed in the area of interest. It has three components, which run sequentially. First, it determines the amount of water running off each pixel as the precipitation minus the fraction of the water that undergoes evapotranspiration. The model does not differentiate between surface, subsurface and baseflow, but assumes that all water yield from a pixel reaches the point of interest via one of these pathways. This model then sums and averages water yield to the subwatershed level. The pixel-scale calculations allow us to represent the heterogeneity of key driving factors in water yield such as soil type, precipitation, vegetation type, etc. However, the theory we are using as the foundation of this set of models was developed at the subwatershed to watershed scale. We are only confident in the interpretation of these models at the subwatershed scale, so all outputs are summed and/or averaged to the subwatershed scale. We do continue to provide pixel-scale representations of some outputs for calibration and model-checking purposes only. **These pixel-scale maps are not to be interpreted for understanding of hydrological processes or to inform decision making of any kind.**

Second, beyond annual average runoff, it calculates the proportion of surface water that is available for hydropower production by subtracting the surface water that is consumed for other uses. Third, it estimates the energy produced by the water reaching the hydropower reservoir and the value of this energy over the reservoir’s lifetime.

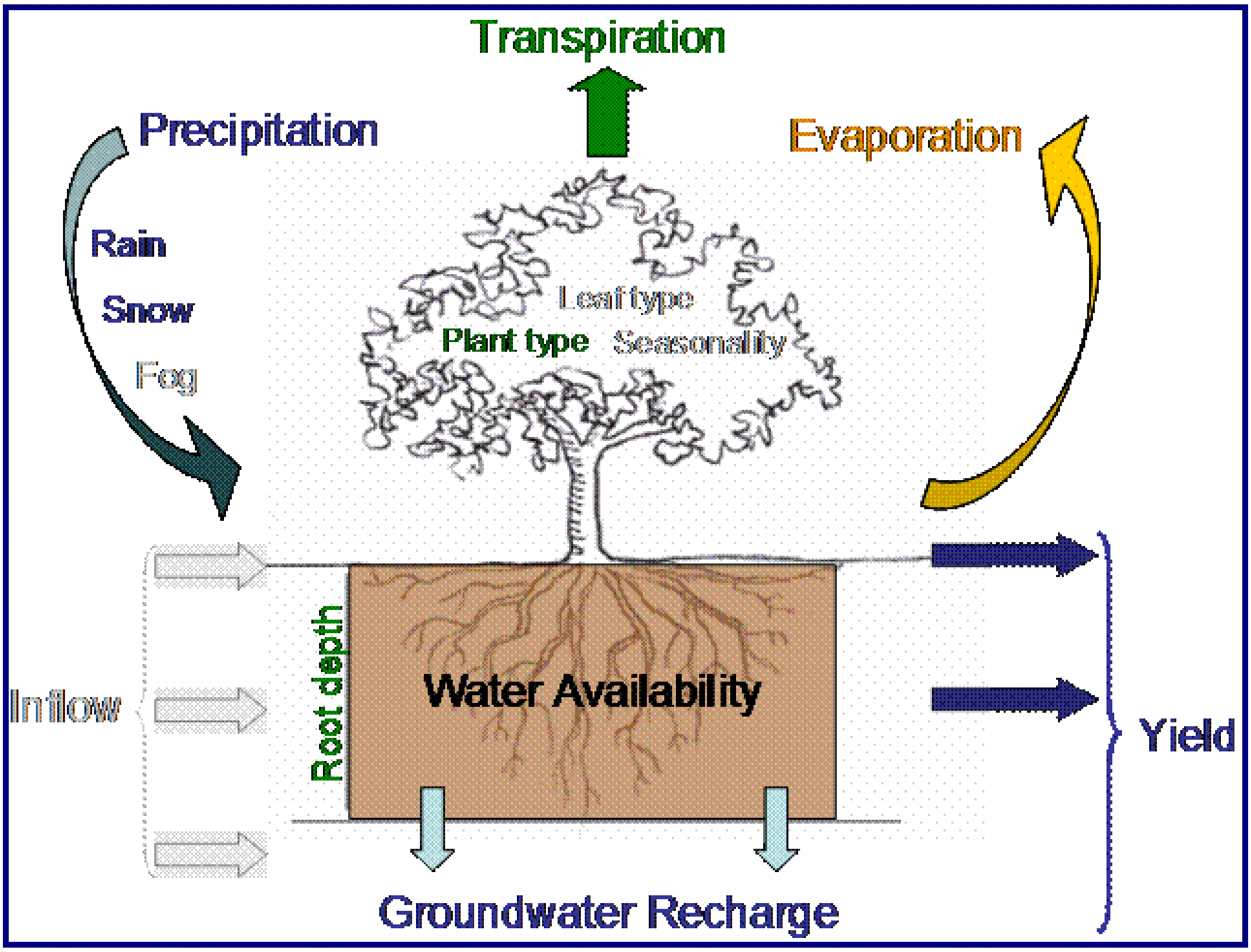

Figure 1. Conceptual diagram of the simplified water balance method used in the annual water yield model. Aspects of the water balance that are in color are included in the model, those that are in grey are not.

Water Yield Model

The water yield model is based on the Budyko curve and annual average precipitation. We determine annual water yield Y(x) for each pixel on the landscape xx as follows:

$Y(x)=(1-AET(x)/P(x))\cdot P(x)$

where AET(x) is the annual actual evapotranspiration for pixel x and P(x) is the annual precipitation on pixel x.

For vegetated land use/land cover (LULC) types, the evapotranspiration portion of the water balance, AET(x)/P(x), is based on an expression of the Budyko curve proposed by Fu (1981) and Zhang et al. (2004):

(1)

$AET(x)/P(x)=1+PET(x)/P(x)-[1+(PET(x)/P(x))\omega]1/\omega$

where PET(x) is the potential evapotranspiration and ω(x) is a non-physical parameter that characterizes the natural climatic-soil properties, both detailed below.

Potential evapotranspiration PET(x) is defined as:

$PET(x)=Kc(\ell x)\cdot ET0(x)$

where, ET0(x) is the reference evapotranspiration from pixel x and Kc(ℓx) is the plant (vegetation) evapotranspiration coefficient associated with the LULC ℓx on pixel x. ET0(x) reflects local climatic conditions, based on the evapotranspiration of a reference vegetation such as grass or alfalfa grown at that location. Kc(ℓx) is largely determined by the vegetative characteristics of the land use/land cover found on that pixel (Allen et al. 1998). Kc adjusts the ET0 values to the crop or vegetation type in each pixel of the land use/land cover map.

ω(x) is an empirical parameter that can be expressed as linear function of AWC∗N/P, where N is the number of rain events per year, and AWC is the volumetric plant available water content (see Appendix 1 for additional details). While further research is being conducted to determine the function that best describe global data, we use the expression proposed by Donohue et al. (2012) in the InVEST model, and thus define:

$\omega(x)=ZAWC(x)/P(x)+1.25$

where:

- AWC(x) is the volumetric (mm) plant available water content. The soil texture and effective rooting depth define AWC(x), which establishes the amount of water that can be held and released in the soil for use by a plant. It is estimated as the product of the plant available water capacity (PAWC) and the minimum of root restricting layer depth and vegetation rooting depth:

$AWC(x)=Min(Rest.layer.depth,root.depth)\cdot PAWC$

Root restricting layer depth is the soil depth at which root penetration is inhibited because of physical or chemical characteristics. Vegetation rooting depth is often given as the depth at which 95% of a vegetation type's root biomass occurs. PAWC is the plant available water capacity, i.e. the difference between field capacity and wilting point.

- Z is an empirical constant, sometimes referred to as "seasonality factor", which captures the local precipitation pattern and additional hydrogeological characteristics. It is positively correlated with N, the number of rain events per year. The 1.25 term is the minimum value of ω(x), which can be seen as a value for bare soil (when root depth is 0), as explained by Donohue et al. (2012). Following the literature (Yang et al., 2008; Donohue et al. 2012), values of ω(x) are capped to a value of 5.

For other LULC types (open water, urban, wetland), actual evapotranspiration is directly computed from reference evapotranspiration ET0(x) and has an upper limit defined by precipitation:

(2)

$AET(x)=Min(Kc(\ell x)\cdot ET0(x),P(x))$

where $ET0(x)$ is reference evapotranspiration, and $Kc(\ell x)$ is the evaporation factor for each LULC.

The water yield model generates and outputs the total and average water yield at the subwatershed level.

Realized Supply

The Realized Supply option of the model (called Water Scarcity in the tool interface) calculates the water inflow to a reservoir based on calculated water yield and water consumptive use in the watershed(s) of interest. The user inputs how much water is consumed by each land use/land cover type in a table format. Examples of consumptive use include municipal or industrial withdrawals that are not returned to the stream upstream of the outlet. This option may also be used to represent inter-basin transfers out of the study watershed.

For example, in an urban area, consumptive use can be calculated as the product of population density and per capita consumptive use. These land use-based values only relate to the consumptive portion of demand; some water use is non-consumptive such as water used for industrial processes or waste water that is returned to the stream after use, upstream of the outlet. Consumptive use estimates should therefore take into account any return flows to the stream above the watershed outlet:

$C=W-R/n$

where, C = the consumptive use (m3/yr/pixel), W = withdrawals (m3/yr), R = return flows (m3/yr), and n = number of pixels in a given land cover.

For simplicity, each pixel in the watershed is either a “contributing” pixel, which contributes to hydropower production, or a “use” pixel, which uses water for other consumptive uses. This assumption implies that land use associated with consumptive uses will not contribute any yield for downstream use. The amount of water that actually reaches the reservoir for dam d (called realized supply) is defined as the difference between total water yield from the watershed and total consumptive use in the watershed:

$Vin=Y-ud$

where Vin is the realized supply (volume inflow to a reservoir), ud is the total volume of water consumed in the watershed upstream of dam d and Y is the total water yield from the watershed upstream of dam d.

Note that only anthropogenic uses are considered here, since evapotranspiration (including consumptive use of water by croplands) are accounted for by the Kc parameter in the water yield model. Users should be aware that the model assumes that all water available for evapotranspiration comes from within the watershed (as rainfall). This assumption holds true in cases where agriculture is either rain-fed, or the source of irrigation water is within the study watershed (not sourced from inter-basin transfer or a disconnected deeper aquifer). See the Limitations section for more information on applying the model in watersheds with irrigated agriculture.

If observed data is available for actual annual inflow rates to the reservoir for dam d, they can be compared to Vin.

Hydropower Production and Valuation

The Valuation option of the model estimates both the amount of energy produced given the estimated realized supply of water for hydropower production and the value of that energy. A present value monetary estimate is given for the entire remaining lifetime of the reservoir. Net present value can be calculated if hydropower production cost data are available. The energy produced and the revenue is then redistributed over the landscape based on the proportional contribution of each subwatershed to energy production. Final output maps show how much energy production and hydropower value can be attributed to each subwatershed's water yield over the lifetime of the reservoir.

An important note about assigning a monetary value to any service is that valuation should only be done on model outputs that have been calibrated and validated. Otherwise, it is unknown how well the model is representing the area of interest, which may lead to misrepresentation of the exact value. If the model has not been calibrated, only relative results should be used (such as an increase of 10%) not absolute values (such as 1,523 cubic meters, or 42,900 dollars.)

At dam d, power is calculated using the following equation:

$$pd=\rho\cdot qd\cdot g\cdot hd$$

where pd is power in watts, ρ is the water density (1000 Kg/m^3), qd is the flow rate (m^3/s), g is the gravity constant (9.81 m/s^2), and hd is the water height behind the dam at the turbine (m). In this model, we assume that the total annual inflow water volume is released equally and continuously over the course of each year.

The power production equation is connected to the water yield model by converting the annual inflow volume adjusted for consumption (Vin) to a per second rate. Since electric energy is normally measured in kilowatt-hours, the power pd is multiplied by the number of hours in a year. All hydropower reservoirs are built to produce a maximum amount of electricity. This is called the energy production rating, and represents how much energy could be produced if the turbines are 100% efficient and all water that enters the reservoir is used for power production. In the real world, turbines have inefficiencies and water in the reservoir may be extracted for other uses like irrigation, retained in the reservoir for other uses like recreation, or released from the reservoir for non-power production uses like maintaining environmental flows downstream. To account for these inefficiencies and the flow rate and power unit adjustments, annual average energy production εd at dam d is calculated as follows:

$$\varepsilon d=0.00272\cdot\beta\cdot\gamma d\cdot hd\cdot Vin$$

where εd is hydropower energy production (KWH), β is the turbine efficiency coefficient (%), γd is the percent of inflow water volume to the reservoir at dam d that will be used to generate energy.

To convert εd, the annual energy generated by dam d, into a net present value (NPV) of energy produced (point of use value) we use the following,

$NPVH_d=(p_e\varepsilon_d-TC_d)\times\sum_{t=0}^{T-1}(1/(1+r)^t)$

where TC_d is the total annual operating costs for dam d, p_e is the market value of electricity (per kilowatt hour) provided by the hydropower plant at dam d, T_d indicates the number of years present landscape conditions are expected to persist or the expected remaining lifetime of the station at dam d (set T to the smallest value if the two time values differ), and r is the market discount rate. The form of the equation above assumes that TC_d, p_e, and ε_d, are constant over time.

Energy production over the lifetime of dam d is attributed to each subwatershed as follows:

$\varepsilon_x=(T_d\varepsilon_d)\times(c_x/c_{tot})$

where the first term in parentheses represents the electricity production over the lifetime of dam dd. The second term represents the proportion of water volume used for hydropower production that comes from subwatershed x relative to the total water volume for the whole watershed. The value of each subwatershed for hydropower production over the lifetime of dam d is calculated similarly:

$NPVH_x=NPVH_d\times(c_x/c_{tot})$

Limitations and Simplifications

The model has a number of limitations. First, it is not intended for devising detailed water plans, but rather for evaluating how and where changes in a watershed may affect hydropower production for reservoir systems. It is based on annual averages, which neglect extremes and do not consider the temporal dimensions of water supply and hydropower production.

Second, the model does not consider the spatial distribution of land use/land cover. The empirical model used for the water balance (based on the Budyko theory) has been tested at larger scales than the pixel dimensions used in InVEST (Hamel & Guswa, in review). Complex land use patterns or underlying geology, which may induce complex water balances, may not be well captured by the model.

Third, the model does not consider sub-annual patterns of water delivery timing. Water yield is a provisioning function, but hydropower benefits are also affected by flow regulation. The timing of peak flows and delivery of minimum operational flows throughout the year determines the rate of hydropower production and annual revenue. Changes in landscape scenarios are likely to affect the timing of flows as much as the annual water yield, and are of particular concern when considering drivers such as climate change. Modeling the temporal patterns of overland flow requires detailed data that are not appropriate for our approach. Still, this model provides a useful initial assessment of how landscape scenarios may affect the annual delivery of water to hydropower production.

Fourth, the model greatly simplifies consumptive demand. For each LULC, a single variable (γ_d) is used to represent multiple aspects of water resource allocation, which may misrepresent the complex distribution of water among uses and over time. In reality, water demand may differ greatly between parcels of the same LULC class. Much of the water demand may also come from large point source intakes, which are not represented by an LULC class at all. The model simplifies water demand by distributing it over the landscape. For example, the water demand may be large for an urban area, and the model represents this demand by distributing it over the urban LULC class. The actual water supply intake, however, is likely further upstream in a rural location. Spatial disparity in actual and modeled demand points may cause an incorrect representation in the realized supply output grid. The distribution of consumption is also simplified in the reallocation of energy production and hydropower value since it is assumed that water consumed along flow paths is drawn equally from every pixel upstream. As a result, water scarcity, energy production patterns, and hydropower values may be incorrectly estimated.

Fifth, water transfers for irrigation, either between subbasins or between seasons, are not well captured by the model. When applying the empirical approach to cropland, irrigation patterns should be considered, which typically fall into one of the following cases:

1. If there is no irrigation other than direct rain, it can be assumed that croplands respond to climate forcing in a similar way to natural vegetation (i.e. the theory behind the eco-hydrological model used in the InVEST model, linking plant available water and climate forcing, applies, cf. Donohue et al. 2012)

2. If small reservoirs store water during the wet season to irrigate crops during the dry season, the AET should equal PET during the irrigation season. However, the model predicts AET<PET due to limited water retention in undisturbed catchments (where there is no other reservoir except soil storage). This likely results in the underestimation of evapotranspiration, and therefore the overestimation of yields. To avoid this issue, you can use the alternative equation for AET (equation 2), which sets AET directly as a function of ETo. (In that case, remember that AET is capped by P to avoid predicting negative water yields, which may result in an overestimation of yields).

3. If the study area contains croplands that are irrigated with water from outside the catchment (either through inter-basin transfer or pumping from a disconnected groundwater source), then AET also equals PET during the irrigation season. Because the model assumes that evapotranspiration is sourced from rainfall, the water yield output is likely overestimated. This situation can also be represented by using the alternative equation for AET (equation 2). Assuming that crops are being irrigated efficiently (i.e. the total volume of imported water is equal to the water deficit, or PET – P, for crop pixels), then the known volume of water irrigated may be added to the modeled water yield to give a better picture of actual yield.

4. Because seasonality can play a significant role in irrigation water use, use caution when applying the annual model in catchments with large irrigated fields. For options that are not covered above or where complex water transfers may substantially affect the water balance, users are encouraged to use alternative models that will better represent the spatial and temporal water transfers. In particular, great caution should be used when calibrating the model without good data on the different water balance components within your study area (i.e. rainfall, streamflow, irrigation rates and timing).

Finally, the model assumes that hydropower production and pricing remain constant over time. It does not account for seasonal variation in energy production or fluctuations in energy pricing, which may affect the value of hydropower. Even if sub-annual production or energy prices change, however, the relative value between parcels of land in the same drainage area should be accurate.

Data Needs

This section outlines the specific data used by the model. See the Appendix for additional information on data sources and pre-processing. Please consult the InVEST sample data (located in the folder where InVEST is installed, if you also chose to install sample data) for examples of all of these data inputs. This will help with file type, folder structure and table formatting. Note that all GIS inputs must be in the same projected coordinate system and in linear meter units.

- **Workspace** (required). Folder where model outputs will be written. Make sure that there is ample disk space, and write permissions are correct.

- **Suffix** (optional). Text string that will be appended to the end of output file names, as "_Suffix". Use a Suffix to differentiate model runs, for example by providing a short name for each scenario. If a Suffix is not provided, or changed between model runs, the tool will overwrite previous results.

- **Precipitation** (required). A GIS raster dataset with a non-zero value for average annual precipitation for each cell. [units: millimeters]

- **Average Annual Reference Evapotranspiration** (required). A GIS raster dataset, with an annual average evapotranspiration value for each cell. Reference evapotranspiration is the potential loss of water from soil by both evaporation from the soil and transpiration by healthy alfalfa (or grass) if sufficient water is available. [units: millimeters]

- **Root restricting layer depth** (required). A GIS raster dataset with an average root restricting layer depth value for each cell. Root restricting layer depth is the soil depth at which root penetration is strongly inhibited because of physical or chemical characteristics. [units: millimeters]

- **Plant Available Water Content** (required). A GIS raster dataset with a plant available water content value for each cell. Plant Available Water Content fraction (PAWC) is the fraction of water that can be stored in the soil profile that is available for plants' use. [fraction from 0 to 1]

- **Land use/land cover** (required). A GIS raster dataset, with an integer LULC code for each cell. These LULC codes must match *lucode* values in the **Biophysical table**.

- **Watersheds** (required). A shapefile, with one polygon per watershed. This is a layer of watersheds such that each watershed contributes to a point of interest where hydropower production will be analyzed. An integer field named *ws_id* is required, with a unique integer value for each watershed.

- **Subwatersheds** (required). A shapefile, with one polygon per subwatershed within the main watersheds specified in the Watersheds shapefile. An integer field named *subws_id* is required, with a unique integer value for each subwatershed.

- **Biophysical Table** (required). A .csv (Comma Separated Value) table containing model information corresponding to each of the land use classes in the LULC raster. *All LULC classes in the LULC raster MUST have corresponding values in this table.* Each row is a land use/land cover class and columns must be named and defined as follows:

  - *lucode* (required): Unique integer for each LULC class (e.g., 1 for forest, 3 for grassland, etc.) **Every value in the LULC map MUST have a corresponding lucode value in the biophysical table.**

  - *LULC_desc* (optional): Descriptive name of land use/land cover class

  - *LULC_veg* (required): Specifies which AET equation to use (Eq. 1 or 2). Values must be 1 for vegetated land use except wetlands, and 0 for all other land uses, including wetlands, urban, water bodies, etc.

  - *root_depth* (required): The maximum root depth for vegetated land use classes, given in integer millimeters. This is often given as the depth at which 95% of a vegetation type's root biomass occurs. For land uses where the generic Budyko curve is not used (i.e. where evapotranspiration is calculated from Eq. 2), rooting depth is not needed. In these cases, the rooting depth field is ignored, and may be set as a value such as -1 to indicate the field is not used.

  - *Kc* (required): Plant evapotranspiration coefficient for each LULC class, used to calculate potential evapotranspiration by using plant physiological characteristics to modify the reference evapotranspiration, which is based on alfalfa. The evapotranspiration coefficient is a decimal in the range of 0 to 1.5 (some crops evapotranspire more than alfalfa in some very wet tropical regions and where water is always available).

- **Z parameter** (required). Floating point value on the order of 1 to 30 corresponding to the seasonal distribution of precipitation (see the Appendix for more information).

- **Demand Table** (required if calculating Water Scarcity or Valuation). A table of LULC classes, with consumptive water use for each landuse/landcover type. Consumptive water use is that part of water used that is incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the watershed water balance. Each row is a land use/land cover class, and columns must be named and defined as follows:

  - *lucode* (required): Unique integer for each LULC class (e.g., 1 for forest, 3 for grassland, etc.), must match the LULC raster above.

  - *demand* (required): The estimated average consumptive water use for each landuse/landcover type. Demand must be given in cubic meters per year per pixel in the land use/land cover map. Note that accounting for pixel area is important since larger pixels will consume more water for the same land cover type.

- **Hydropower valuation table** (required if doing Valuation). A table of hydropower stations (which are the outlets of the input Watersheds) with associated model values. Each row is a hydropower station, and columns must be named and defined as follows:

  - *ws_id* (required): Unique integer value for each hydropower station, which must correspond to values in the Watersheds layer.

  - *station_desc* (optional): Name of hydropower station

  - *efficiency* (required): Turbine efficiency, obtained from the hydropower plant manager. Floating point values (generally 0.7 to 0.9).

  - *fraction* (required): The fraction of inflow water volume that is used to generate energy, obtained from the hydropower plant manager. Managers can release water without generating electricity to satisfy irrigation, drinking water or environmental demands. Floating point value.

  - *height* (required): The head, measured as the average annual effective height of water behind each dam at the turbine intake. Floating point value in meters.

  - *kw_price* (required): The price of one kilowatt-hour of power produced by the station, in any currency (but must match the currency used for *cost*.) Floating point value.

  - *cost* (required): Annual cost of running the hydropower station (maintenance and operations costs), in any currency (but must match the currency used for *kw_price*.) Floating point value.

  - *time_span* (required): Either the expected lifespan of the hydropower station or the period of time of the land use scenario of interest. Used in net present value calculations. Integer value.

  - *discount* (required): The discount rate over the time span, used in net present value calculations. Percentage - for example, if the discount rate is 5%, enter the value 5.

Running the Model

To launch the Water Yield model navigate to the Windows Start Menu -> All Programs -> InVEST [*version*] -> Water Yield. The interface does not require a GIS desktop, although the results will need to be explored with any GIS tool such as ArcGIS or QGIS. By default, only the biophysical (water yield) portion of the model will be run. If you want to also use Water Scarcity and Valuation, check the box next to these options and fill in the additional data. Water Scarcity may be run alone, but if running Valuation, Water Scarcity must also be run.

This model supports avoided re-computation. This means the model will detect intermediate and final results from a previous run in the specified workspace and it will avoid re-calculating any outputs that are identical to the previous run. This can save significant processing time for successive runs when only some input parameters have changed.

Interpreting Results

The following is a short description of each of the outputs from the Water Yield model. Final results are found within the user defined Workspace specified for this model run. "Suffix" in the following file names refers to the optional user-defined Suffix input to the model.

- **Parameter log**: Each time the model is run, a text (.txt) file will be created in the Workspace. The file will list the parameter values and output messages for that run and will be named according to the service, the date and time. When contacting NatCap about errors in a model run, please include the parameter log.

- Outputs in the *per_pixel* folder can be useful for intermediate calculations but should **NOT** be interpreted at the pixel level, as model assumptions are based on processes understood at the subwatershed scale.

    - **output\per_pixel\fractp_[Suffix].tif** (fraction): Estimated actual evapotranspiration fraction of precipitation per pixel (Actual Evapotranspiration / Precipitation). It is the mean fraction of precipitation that actually evapotranspires at the pixel level.

    - **output\per_pixel\aet_[Suffix].tif** (mm): Estimated actual evapotranspiration per pixel.

    - **output\per_pixel\wyield_[Suffix].tif** (mm): Estimated water yield per pixel.

- **output\subwatershed_results_wyield_[Suffix].shp** and **output\subwatershed_results_wyield_[Suffix].csv**: Shapefile and table containing biophysical output values per subwatershed, with the following attributes:

    - *precip_mn* (mm): Mean precipitation per pixel in the subwatershed.

    - *PET_mn* (mm): Mean potential evapotranspiration per pixel in the subwatershed.

    - *AET_mn* (mm): Mean actual evapotranspiration per pixel in the subwatershed.

    - *wyield_mn* (mm): Mean water yield per pixel in the subwatershed.

    - *wyield_vol* (m^3): Volume of water yield in the subwatershed.

- **output\watershed_results_wyield_[Suffix].shp** and **output\watershed_results_wyield_[Suffix].csv**: Shapefile and table containing output values per watershed, with the following attributes:

    - *precip_mn* (mm): Mean precipitation per pixel in the watershed.

    - *PET_mn* (mm): Mean potential evapotranspiration per pixel in the watershed.

    - *AET_mn* (mm): Mean actual evapotranspiration per pixel in the watershed.

    - *wyield_mn* (mm): Mean water yield per pixel in the watershed.

    - *wyield_vol* (m^3): Volume of water yield in the watershed.

If the Water Scarcity option is run, the following attributes will also be included for watersheds and subwatersheds:

- **consum_vol** (m^3): Total water consumption for each watershed.
- **consum_mn** (m^3/ha): Mean water consumptive volume per hectare per watershed.
- **rsupply_vl** (m^3): Total realized water supply (water yield – consumption) volume for each watershed.
- **rsupply_mn** (m^3/ha): Mean realized water supply (water yield – consumption) volume per hectare per watershed.

If the Valuation option is run, the following attributes will also be included for watersheds, but not for subwatersheds:

- **hp_energy** (kw/timespan): The amount of ecosystem service in energy production terms. This shows the amount of energy produced by the hydropower station over the specified timespan that can be attributed to each watershed based on its water yield contribution.
- **hp_val** (currency/timespan): The amount of ecosystem service in economic terms. This shows the value of the landscape per watershed according to its ability to yield water for hydropower production over the specified timespan.

- **intermediate**: This directory contains data that represent intermediate steps in calculations of the final data in the output folder. It also contains subdirectories that store metadata used internally to enable avoided re-computation.

The application of these results depends entirely on the objective of the modeling effort. Users may be interested in all of these results or a select one or two. If valuation information is not available or of interest, you may choose to simply run the water yield model and compare biophysical results.

The first several model results provide insight into how water is distributed throughout the landscape. *aet_mn* describes the actual evapotranspiration depth of the hydrologic cycle, showing how much water (precipitation) is lost annually to evapotranspiration across the watershed or subwatershed.

The *wyield_vol* field contains the estimated annual average water volume that is 'yielded' from each subwatershed within the watershed of interest. This value can be used to determine which subwatersheds are most important to total annual water yield – although at this step the user still will not know how much of that water is benefiting downstream users of any type. The consumptive use (*consum_vol*) field then shows how much water is used for consumptive activities (such as drinking, bottling, etc.) each year across the landscape per watershed. The realized supply (*rsupply_vl*) field contains the difference between cumulative water yield and cumulative consumptive use. This value demonstrates where the water supply for hydropower production is abundant and where it is most scarce. Remember that the consumptive use value may not truly represent where water is taken, only where it is demanded. This may cause some misrepresentation of the scarcity in certain locations, but this value offers a general sense of the water balance and whether there is a lack of or abundance of water in the watershed of interest.

The *hp_energy* and *hp_val* values are the most relevant model outputs for prioritizing the landscape for investments that wish to maintain water yield for hydropower production. The *hp_val* field contains the most information for this purpose as it represents the revenue attributable to each watershed over the expected lifetime of the hydropower station, or the number of years that the user has chosen to model. This value accounts for the fact that different hydropower stations within a large river basin may have different customers who pay different rates for energy production. If this is the case, this result will show which watersheds contribute the highest value water for energy production. If energy values do not vary much across the landscape, the *hp_energy* outputs can be just as useful in planning and prioritization. Comparing any of these values between landuse scenarios allows you to understand how the role of the landscape may change under different management plans.

Appendix 1: Data Sources

This is a rough compilation of data sources and suggestions about finding, compiling, and formatting data, providing links to global datasets that can get you started. It is highly recommended to look for more local and accurate data (from national, state, university, literature, NGO and other sources) and only use global data for final analyses if nothing more local is available.

Average annual precipitation

Average Annual Precipitation may be interpolated from existing rain gage point data, and global data sets from remote sensing models to account for remote areas. Precipitation as snow is included. When considering rain gage data, make sure that they provide good coverage over the area of interest, especially if there are large changes in elevation that cause precipitation amounts to be heterogeneous within the study area. Ideally, the gauges will have at least 10 years of continuous data, with no large gaps, around the same time period as the land use/land cover map used as input.

If field data are not available, you can use coarse data from the freely available global data sets developed by the Climatic Research Unit: http://www.cru.uea.ac.uk or WorldClim: http://www.worldclim.org/.

Within the United States, the PRISM group at Oregon State University provides free precipitation data at a 30-arcsecond resolution. See their website at http://www.prism.oregonstate.edu/ and navigate to ‘800m Normals’ to download data.

Average annual reference evapotranspiration (ET0ET0**)**

Reference evapotranspiration, ET0ET0, is the energy (expressed as a depth of water, e.g. mm) supplied by the sun (and occasionally wind) to vaporize water. Reference evapotranspiration varies with elevation, latitude, humidity, and slope aspect. There are many methodologies, which range in data requirements and precision.

CGIAR provides a global map of potential evapotranspiration, based on WorldClim climate data, which may be used for reference ET: https://cgiarcsi.community/data/global-aridity-and-pet-database/.

You can calculate reference ET by developing monthly average grids of precipitation, and maximum and minimum temperatures. These data can come from weather stations, where you can follow the same process as the development of the average annual precipitation grid, including incorporating the effects of elevation when interpolating between stations. Or, both WorldClim and CRU provide monthly temperature data already in grid format. These monthly grids can be used as input to the equations listed below.

A simple way to determine reference evapotranspiration is the 'modified Hargreaves' equation (Droogers and Allen, 2002), which generates superior results than the Pennman-Montieth when information is uncertain.

$ET0=0.0013\times0.408\times RA\times(Tav+17)\times(TD-0.0123P)0.76$

The 'modified Hargreaves' method uses the average of the mean daily maximum and mean daily minimum temperatures for each month (Tavg in degrees Celsius), the difference between mean daily maximum and mean daily minimums for each month (TD), RA is extraterrestrial radiation (RA in $MJm-2d-1MJm-2d-1$ and precipitation (P in mm per month), all of which can be relatively easily obtained. Temperature and precipitation data are often available from regional charts, direct measurement or national or global datasets. Radiation data, on the other hand, is far more expensive to measure directly but can be reliably estimated from online tools, tables or equations. FAO Irrigation Drainage Paper 56 provides monthly radiation data in Annex 2.

The reference evapotranspiration can also be calculated monthly and annually using the Hamon equation (Hamon 1961, Wolock and McCabe 1999):

$PEDHamon=13.97dD2Wt$

where *d* is the number of days in a month, *D* is the mean monthly hours of daylight calculated for each year (in units of 12 hours), and Wt is a saturated water vapor density term calculated by:

$Wt=4.95e0.062T100$

where T is the monthly mean temperature in degrees Celsius. Reference evapotranspiration is set to zero when mean monthly temperature is below zero. Then for each year during the time period analyzed, the monthly calculated PET values at each grid cell are summed to calculate a map of the annual PET for each year.

A final method to assess ETo, when pan evaporation data are available, is to use the following equation: ETo = (pan ET)*0.7 (Allen et al., 1998)

Root restricting layer depth

Root restricting layer depth is the soil depth at which root penetration is strongly inhibited because of physical or chemical characteristics. Root restricting layer depth may be obtained from some soil maps. If root restricting layer depth or rootable depth by soil type is not available, soil depth can be used as a proxy. If several soil horizons are detailed, the root restricting layer depth is the sum of the depths of non-restrictive soil horizons.

Global soil data are available from the Soil and Terrain Database (SOTER) Programme (http://data.isric.org). They provide some area-specific soil databases, as well as SoilGrids globally (https://www.isric.org/index.php/explore/soilgrids.)

The FAO also provides global soil data in their Harmonized World Soil Database: http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/, but it is rather coarse.

In the United States free soil data is available from the U.S. Department of Agriculture's NRCS SSURGO database: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627

The Soil Data Viewer (http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/home/?cid=nrcs142p2_053620) contains an ArcGIS extention that helps with pre-processing and downloading of the data. Highly recommended if you use ArcGIS and need to process U.S. soil data.

Plant available water content (PAWC)

Plant available water content is a fraction obtained from some standard soil maps. It is defined as the difference between the fraction of volumetric field capacity and permanent wilting point. Often plant available water content is available as a volumetric value (mm). To obtain the fraction divide by soil depth. Soil characteristic layers are estimated by performing a weighted average from all horizons within a soil component. If PAWC is not available, raster grids obtained from polygon shape files of weight average soil texture (%clay, %sand, %silt) and soil porosity will be needed. See 'Root Restricting Layer Depth' above for a description of where to find and how to process soil data. https://www.ars.usda.gov/research/software/download/?softwareid=492 has software to help you estimate PAWC when you have soil texture data.

Land use/land cover

A key component for all water models is a spatially continuous land use/land cover (LULC) raster, where all pixels must have a land use/land cover class defined. Gaps in data will create missing data (holes) in the output layers. Unknown data gaps should be approximated.

Global land use data is available from:

- NASA: https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mcd12q1 (MODIS multi-year global landcover data provided in several classifications)
- The European Space Agency: https://www.esa-landcover-cci.org (Three global maps for the 2000, 2005 and 2010 epochs)
- The University of Maryland's Global Land Cover Facility: http://glcf.umd.edu/data/landcover/ (data available in 1 degree, 8km and 1km resolutions).

Data for the U.S. is provided by the USGS and Department of the Interior via the National Land Cover Database: https://www.mrlc.gov/finddata.php

The simplest categorization of LULCs on the landscape involves delineation by land cover only (e.g., cropland, forest, grassland). Several global and regional land cover classifications are available (e.g., Anderson et al. 1976), and often detailed land cover classification has been done for the landscape of interest.

A slightly more sophisticated LULC classification involves breaking relevant LULC types into more meaningful types. For example, agricultural land classes could be broken up into different crop types or forest could be broken up into specific species. The categorization of land use types depends on the model and how much data is available for each of the land types. You should only break up a land use type if it will provide more accuracy in modeling. For instance, only break up 'crops' into different crop types if you have information on the difference in evapotranspiration rates (Kc) and root depth between crop values.

Sample Land Use/Land Cover Table

lucode	Land Use/Land Cover
1	Evergreen Needleleaf Forest
2	Evergreen Broadleaf Forest
3	Deciduous Needleleaf Forest
4	Deciduous Broadleaf Forest
5	Mixed Cover
6	Woodland
7	Wooded Grassland
8	Closed Shrubland
9	Open Shrubland
10	Grassland

lucode	Land Use/Land Cover
11	Cropland (row Crops)
12	Bare Ground
13	Urban and Built-Up
14	Wetland
15	Mixed evergreen
16	Mixed Forest
17	Orchards/Vineyards
18	Pasture

Root depth

A valuable review of plant rooting depths was done by Schenk and Jackson (2002). Root depth values should be based on depth at which 90% of root biomass occurs, not the maximum depth of the longest tap root. Other rooting depth values for crops and some tree plantations can be found in the FAO 56 guidelines by Allen et al. (1998).

The model determines the minimum of root restricting layer depth and rooting depth for an accessible soil profile for water storage. Values must be integer, converted to mm. For non-vegetated LULCs (e.g. urban), for which Equation 2 above is used, the model will not use the root depth value so any value can be inserted into the table.

Evapotranspiration coefficient Kc

Evapotranspiration coefficient (Kc) values for crops are readily available from irrigation and horticulture handbooks. FAO has an online resource for this: http://www.fao.org/docrep/X0490E/x0490e0b.htm. The FAO tables list coefficients by crop growth stage (Kc ini, Kc mid, KcKc end), which need to be converted to an annual average Kc. This requires knowledge about the phenology of the vegetation in the study region (average green-up, die-down dates) and crop growth stages (when annual crops are planted and harvested). Annual average Kc can be estimated as a function of vegetation characteristics and average monthly reference evapotranspiration using the following equation:

Kc=∑12m=1Kcm×ETom/∑12m=1ETom

where Kcm is an average crop coefficient of month mm (1-12) and ETom is the corresponding reference evapotranspiration. These values can also be calculated using the following spreadsheet: http://data.naturalcapitalproject.org/invest-data/Kc_calculator.xlsx. Values for Kc should be decimals between 0-1.5.

Values for other vegetation types can be estimated using Leaf Area Index (LAI) relationships. LAI characterizes the area of green leaf per unit area of ground surface and can be obtained by satellite imagery products derived from NDVI analysis. A typical LAI - Kc relationship is as follows (Allen et al., 1998, Chapter 6: http://www.fao.org/docrep/x0490e/x0490e0b.htm):

Kc={LAI3 when LAI≤3

1

Kc estimates for non-vegetated LULC are based on (Allen et al., 1998). Note that these values are only approximate, but unless the LULC represents a significant portion of the watershed, the impact of the approximation on model results should be minimal.

- Kc for <2m open water can be approximated by Kc=1;
- Kc for >5m open water is in the range of 0.7 to 1.1;
- Kc for wetlands can be assumed in the range of 1 to 1.2;
- Kc for bare soil ranges from 0.3 to 0.7 depending on climate (in particular rainfall frequency). It can be estimated at Kc=0.5 (see Allen 1998, Chapter 11). Additional information for determining Kc for bare soil can be found in (Allen et al., 2005).
- Kc for built areas can be set to f*0.1 +(1-f)*0.6 where f is the fraction of impervious cover in the area. Here, evapotranspiration from pervious areas in built environments is assumed to be approximately 60% of reference evapotranspiration (i.e. the average between lawn grass and bare soil). In addition, evaporation from impervious surface is assumed at 10% of PET. Should local data be available, the user may compute an annual average estimate of Kc, using the method described for crop factors.

No zero values are allowed.

Consumptive water use

The consumptive water use for each land use/land cover class is the water that is removed from the water balance. It should be estimated based on knowledge of local water transfers (e.g. extraction from groundwater or surface water for urban water supply) in consultation with local professionals in these fields. The value used in the table is an average for each land use type. For agricultural areas, water used by cattle or agricultural processing that is not returned to the watershed must be considered. In urban areas, water use may be calculated based on an estimated water use per person and multiplied by the approximate population area per raster cell. Industrial water use or water exports to other watersheds must also be considered where applicable. For all of these calculations, it is assumed that the agricultural water demand, people, etc. are spread evenly across each land use class.

Watersheds / subwatersheds

To delineate watersheds, we provide the InVEST tool DelineateIT, which is relatively simple yet fast and has the advantage of creating watersheds that might overlap, such as watersheds draining to several dams on the same river. See the User Guide chapter for DelineateIt for more information on this tool. Watershed creation tools are also provided with GIS software, as well as some hydrology models. It is recommended that you delineate watersheds using the DEM that you are modeling with, so the watershed boundary corresponds correctly to the topography.

Alternatively, a number of watershed maps are available online, e.g. HydroBASINS: http://hydrosheds.org/. Note that if watershed boundaries are not based on the same DEM that is being modeled, results that are aggregated to these watersheds are likely to be inaccurate.

Exact locations of specific structures, such as drinking water facility intakes or reservoirs, should be obtained from the managing entity or may be obtained on the web:

- The U.S. National Inventory of Dams: http://nid.usace.army.mil/
- Global Reservoir and Dam (GRanD) Database: http://www.gwsp.org/products/grand-database.html
- World Water Development Report II dam database: http://wwdrii.sr.unh.edu/download.html

Some of these datasets include the catchment area draining to each dam, which should be compared with the area of the watershed(s) generated by the delineation tool to assess accuracy.

Hydropower Station Information

Detailed information about each hydropower station may only be available from the owner or managing entity of the stations. Some information may be available through public sources, and may be accessible online. In particular, if the hydropower plant is located in the United States some information may be found on the internet.

Exact locations of specific structures, such as reservoirs, should be obtained from the managing entity or may be obtained on the web:

- The U.S. National Inventory of Dams: http://nid.usace.army.mil/
- Global Reservoir and Dam (GRanD) Database: http://www.gwsp.org/products/grand-database.html
- World Water Development Report II dam database: http://wwdrii.sr.unh.edu/download.html

- *Calibration*: For calibration, data are needed on how much water actually reaches the (sub)watershed outlets, which can be a hydropower station, on an average annual basis. Data should be available from the managing entity of the hydropower plant. In absence of information available directly from the hydropower operators, data may be available for a stream gage just upstream of the hydropower station. Gages in the U.S. may be managed by the USGS, the state fish and wildlife agency, the state department of ecology or by a local university.

- *Time_period*: The design life span of each hydropower station can be obtained from the station owner or operator. Alternative sources may be available online as described above. This value may instead represent the time period of a scenario of interest, which should be equal to or smaller than the life span of the station.

- *Discount_rate*: This rate is defined as how much value the currency loses per year, which reflects society's preference for immediate benefits over future benefits.

Z parameter

Z is an empirical constant that captures the local precipitation pattern and hydrogeological characteristics, with typical values ranging from 1 to 30. Several studies have determined ωω empirically (e.g. Xu et al. 2013, Fig. 3; Liang and Liu 2014; Donohue et al. 2012) and can be used to estimate Z. The relationship between ωω and Z is:

$Z=(\omega-1.25)P/AWC$

where P and AWC should be average values of Precipitation and Available Water Capacity, respectively, in the study area. AWC is the volumetric (mm) plant available water content. The soil texture and effective rooting depth define AWC, which establishes the amount of water that can be held and released in the soil for use by a plant. It is estimated as the product of the plant available water capacity (PAWC) and the minimum of root restricting layer depth and vegetation rooting depth:

$AWC=Min(Rest.layer.depth,root.depth)\times PAWC$

Root restricting layer depth is the soil depth at which root penetration is inhibited because of physical or chemical characteristics. Vegetation rooting depth is often given as the depth at which 95% of a vegetation type's root biomass occurs. PAWC is the plant available water capacity, i.e. the difference between field capacity and wilting point.

Alternatively, following a study by Donohue et al. (2012) encompassing a range of climatic conditions in Australia, Z could be estimated as 0.2*N, where N is the number of rain events per year. The definition of a rain event is the one used by the authors of the study, characterized by a minimum period of 6 hours between two storms. Calibration of the Z coefficient may also be used by comparing modeled and observed data. Note that the Budyko curve theory suggests that the sensitivity of the model to Z is lower when Z values are high, or in areas with a very low or very high aridity index (ET0/P; see Fig. 5 in Zhang et al. 2004).

Appendix 2: Calibration of Water Yield Model

The water yield model is based on a simple water balance where it is assumed that all water in excess of evaporative loss arrives at the outlet of the watershed. The model is an annual average time step simulation tool applied at the pixel level but reported at the subwatershed level. If possible, calibration of the model should be performed using long term average streamflow. As a rule of thumb, a 10-year period should be used to capture some climate variability, and this 10-year period should coincide with the date of the LULC map. Gauge data is often provided in flow units (such as m^3/s). Since the model calculates water volume, the observed flow data should be converted into units of m^3/year. Climate data (total precipitation and potential evapotranspiration) should also match the date of the land use map. The other inputs, root restricting layer depth and plant available water content are less susceptible to temporal variability so any available data for these parameters may be used.

As with all models, model uncertainty is inherent and must be considered when analyzing results for decision making. Before starting the calibration process, we highly recommend conducting a sensitivity analysis. The sensitivity analysis will define the parameters that influence model outputs the most (see for example Hamel and Guswa 2015; Sanchez-Canales et al., 2012). The calibration can then focus on highly sensitive parameters.