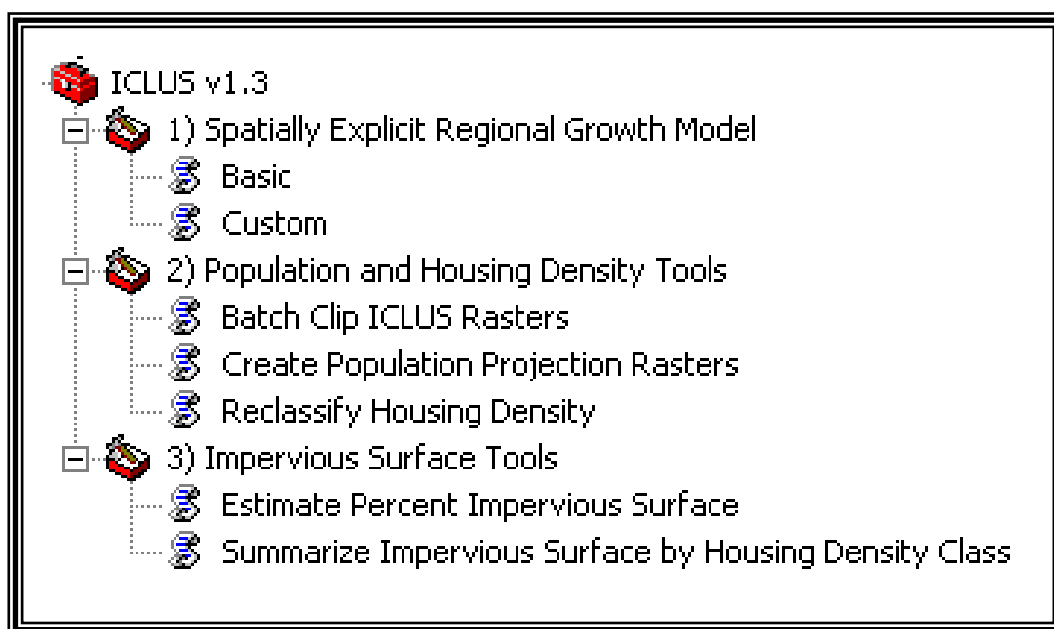


INTEGRATED CLIMATE AND LAND-USE SCENARIOS (ICLUS) v1.3 USER'S MANUAL: ARCGIS TOOLS AND DATASETS FOR MODELING US HOUSING DENSITY GROWTH



Global Change Research Program
National Center for Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

DISCLAIMER

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Preferred Citation:

U.S. Environmental Protection Agency (EPA). 2010. ICLUS v1.3 User's Manual: ArcGIS Tools and Datasets for Modeling US Housing Density Growth. Global Change Research Program, National Center for Environmental Assessment, Washington, DC; EPA/600/R-09/143F. Available from the National Technical Information Service, Springfield, VA, and online at <http://www.epa.gov/ncea/global>.

CONTENTS

Contents	iii
Tables	iii
Figures.....	iv
Authors and Reviewers	v
1. Purpose.....	1
1.1 Key assumptions and uses	1
2. Software, hardware, and experience requirements	2
2.1. Technical description of SERGoM v3.....	3
2.2. SRES-specific parameters for SERGoM	7
3. Tools	10
3.1. Setting Up The ICLUS Tools	10
3.2. SERGoM: The Spatially Explicit Regional Growth Model	11
3.2.1 Basic SERGoM.....	12
3.2.2 Customized SERGoM.....	13
3.3. Batch Clip ICLUS Rasters	13
3.4. Create Population Projection Rasters.....	14
3.5. Reclassify Housing Density to Classes.....	15
3.6. Estimate Percent Impervious Surface	16
3.7. Summarize Impervious Surface By Housing Density Class	17
4. References.....	19

TABLES

Table 2-1. Description of the weights that are applied to NLCD which are used to allocate the block housing units within each block.....	6
Table 2-2. Summary of Adjustments to SERGoM v3 for SRES scenarios.....	8

FIGURES

Figure 2-1. Diagram of SERGoM data inputs and modeling process	4
Figure 3-1: Loading the ICLUS Toolbox into ArcGIS.....	10
Figure 3-2: The Expanded ICLUS Tools.....	11
Figure 3-3: Basic SERGoM User Interface	12
Figure 3-4: Custom SERGoM User Interface.....	13
Figure 3-5: Opening Screen for the Batch Clip ICLUS Rasters Tool	14
Figure 3-6: Opening Screen for Create Population Projection Rasters Tool.....	15
Figure 3-7: Opening Screen for the Reclassify Housing Density Tool	16
Figure 3-8: Opening Screen for the Estimate Percent Impervious Surface Tool	17
Figure 3-9: Opening Screen for the Summarize Impervious Surface by Housing Density Class Tool.....	18

AUTHORS AND REVIEWERS

The Global Change Research Program, within the National Center for Environmental Assessment, Office of Research and Development, is responsible for publishing this report. This document was prepared by ICF International under Contract No. GS-10F-0234J, U.S. EPA Order No. 1101 and Interagency Agreement RW-14-92237501-0 with the U.S. Geological Survey, and by Dr. David M. Theobald, Colorado State University, through a sub-contract on these awards. Dr. Chris Pyke and Dr. Britta Bierwagen served as successive Technical Project Officers. Drs. Pyke and Bierwagen provided overall direction and technical assistance.

AUTHORS

Natural Resource Ecology Lab, Colorado State University, Fort Collins, CO

David M. Theobald

U.S. EPA, Washington, D.C.

Philip Morefield

ICF International

Mark Bethoney, Chris Hogan, and Kevin Wright

REVIEWERS

U.S. EPA Reviewers

Jason Berner, Walt Foster, Gordon Hamilton

External Reviewers

Chansheng He (Western Michigan University), Victor Mesev (Florida State University),
Ningchuan Xiao (The Ohio State University)

ACKNOWLEDGEMENTS

We would like to thank reviewers for testing and evaluating these geoprocessing tools and providing valuable feedback on usability and enhancements.

1. PURPOSE

The purpose of this document is to describe the tools and models generated for the Integrated Climate and Land Use Scenarios (ICLUS) project led by the US EPA's Global Change Research Program in the Office of Research and Development's National Center for Environmental Assessment (USEPA 2009). The tools and models described in this document provide users with the ability to generate, visualize, and analyze spatial datasets about residential housing growth in the coterminous US.

ICLUS consists of a demographic and a spatial allocation model. The tools described in this document use output from the demographic model, but do not allow modifications to that model. The tools do, however, provide users with the ability to modify some of the parameters of the spatial allocation model.

The spatial allocation model used in this project is SERGoM, the Spatially Explicit Regional Growth Model, which has been under development for nearly a decade, and a number of papers describe it more fully (Theobald 2001, 2003, 2005). It has been used for a number of applications to assess effects on other land cover classes or environmental variables, including the Forests on the Edge project, which examines effects of housing density changes on forest products and services (Stein et al. 2005, 2007). Unlike the majority of land use change models focusing on urban growth, SERGoM uses and models a full continuum of housing density, from urban to rural. This allows a more comprehensive examination of growth patterns, since exurban/low-density development has become more prevalent in the past decades and is an important aspect of possible future growth scenarios. SERGoM is based on a relatively high resolution (1 ha) representation of land-use patterns, but is best applied at a regional to national extent. This is because there are relatively few assumptions underlying the model – it is not a data-rich approach (e.g., agent-based modeling). Semi-decadal population projections for each county drive the production of new housing units, which are allocated in response to the spatial pattern of growth during the previous time step, transportation infrastructure, and other basic assumptions. An important technical advantage of this model is that it provides a consistent, comprehensive, nationwide model at 1 ha resolution.

1.1 KEY ASSUMPTIONS AND USES

As with any model, there are a number of key assumptions that should be understood when using the SERGoM model and results. In particular, these assumptions are:

- future growth will be similar to those patterns experienced during the previous times step
- this approach is applicable to understanding regional and broader-scale development patterns, it is not suitable for finer-scale analysis;
- projected population level of a county is the major driver of growth, particularly in the long term;
- only residential housing density is estimated – other land uses typically considered to be part of urbanization are industrial, commercial, or transportation land uses and are not modeled;
- housing units are added – a loss of housing units due to conversion to commercial or demolition is not modeled;

Although there are a large number of possible uses, the tools provided in the ICLUS v1.3 toolset are designed to assist with, at a minimum, the following common anticipated user scenarios:

- access the county-level ICLUS population projections;
- customize housing density patterns by altering household size and travel time assumptions;
- classify housing density into generalized categories;
- estimate future impervious surface cover based on housing density; and
- summarize levels of imperviousness by housing density classes.

Note that we originally intended to develop a tool to compute population density from housing density. However, in developing such a tool, we discovered that there can be some numerical instability issues because of the sensitivity of the assumption about people per housing unit (household size) that is used as a multiplier to convert housing units to population.

2. SOFTWARE, HARDWARE, AND EXPERIENCE REQUIREMENTS

These tools were designed, created, and tested using ArcGIS 9.3.1. The geoprocessing-script tools require the Spatial Analyst extension and Python 2.5.1, which is installed by default with ArcGIS 9.3.1. Because this is a complex spatial model with numerous large (fine-grain, broad-extent) spatial datasets, a high-end computing environment is highly recommended. At a minimum, this means 4GB RAM with multiple CPU cores. It is also highly recommended that

50-100 GB of disk space be available to accommodate large output files (~600 MB each) and intermediate files created during processing. Hardware for high-speed input/output (e.g. RAID 0) may improve processing times, particularly for the SERGoM model. The experience level of the GIS analyst using these tools should be advanced (at least 3 years experience), with knowledge of raster datasets and spatial modeling, and experience with very large datasets.

2.1. TECHNICAL DESCRIPTION OF SERGOM V3

SERGoM, unlike the majority of land use change models, allocates a full continuum of housing density, from urban to rural. This allows a more comprehensive examination of growth patterns, since exurban/low-density development generally has a footprint 10 times as large as urban areas and is growing at a faster rate than urban areas (Theobald 2005). In addition, SERGoM forecasts housing development by establishing a relationship between neighboring housing density, population growth rates, and transportation infrastructure (Theobald 2005). The model is dynamic in that as new urban-core areas emerge, the model re-calculates travel time from these areas. However, the expected changes in functional connectivity that would result from such emerging urbanization were not fed back into the functional connectivity calculations used to calculate domestic migration. SERGoM also incorporates a detailed layer of developable/un-developable areas that incorporates public protected lands as well as private protected (e.g., through conservation easements) lands. Finally, population forecasts are a principal driver of SERGoM; in the model, population growth is converted to housing units, which are spatially allocated in response to the spatial pattern of previous growth and transportation infrastructure (Figure 2-1). Growth rates and other model parameters can be user-specified and are spatially explicit, so different regions (even census tracts or neighborhoods) can have different parameters (e.g., lower household size in amenity areas, etc.). The benefit of this approach is that there are fewer discrete differences across artificial analytical boundaries imposed by “piecing” individual model runs into a nationwide map, although the allocation of new housing units takes place on a county-by-county basis.

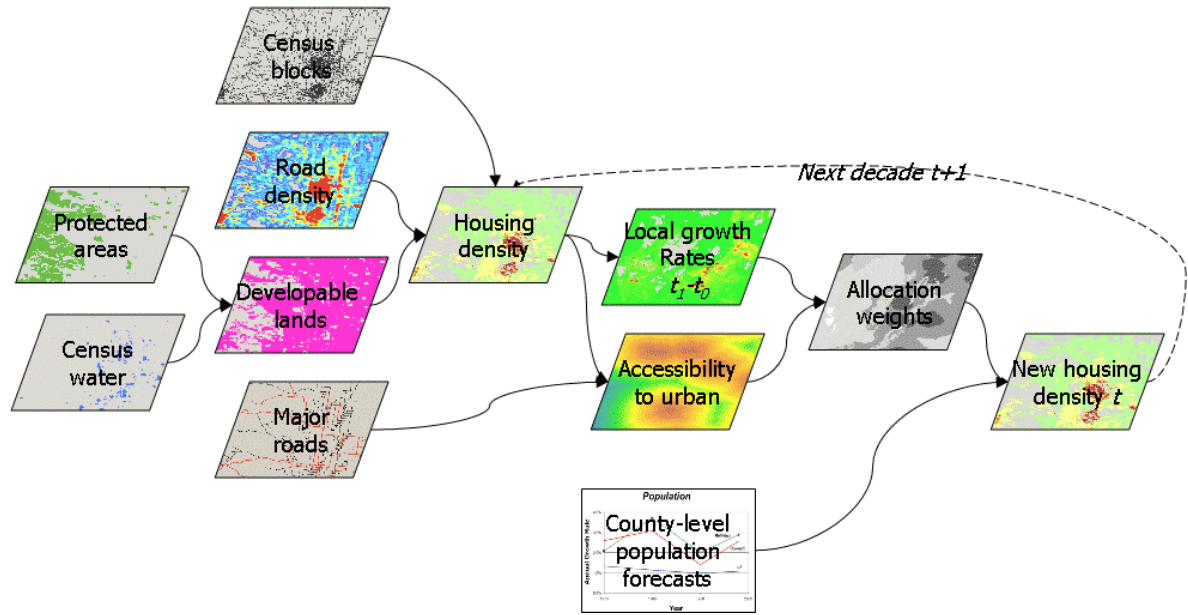


Figure 2-1. Diagram of SERGoM data inputs and modeling process

Housing density (number of housing units per acres) was computed for each 1 ha cell (100 m x 100 m raster; 2.47 acres). There are five main input spatial datasets used to estimate housing density:

1. 2000 Census Bureau – Data were compiled from the 2000 census on the number of housing units and population for each block in the year 2000 and the geography or polygon boundary for each census block (from the Summary File 1 dataset). Block-groups, which are a coarser-level aggregation of block polygons, and attributes of the number of housing units built by decade were used to estimate the historical number of housing units in each block. An operating assumption in estimating historical housing units is that they have not declined over time, so that the number of housing units in any past decade (back to 1940) did not exceed the number of units in any subsequent decade (up to 2000). Reservoirs, lakes, and wide rivers that were identified as “water blocks” were also removed, so that no housing units were placed in these undevelopable areas.
2. Undevelopable lands – Spatial data on land ownership were compiled from a variety of sources to create the most current and comprehensive dataset – called the UPPT (unprotected, private protected, public protected, and tribal/native lands). The UPPT dataset was generated by starting with the Conservation Biology Institute’s PAD-US database. We updated the PAD-US dataset with more current data for 21 states. The operating assumption is that housing units do not occur on publicly owned lands (e.g., national parks, forests, state

wildlife areas, etc.) or on privately-owned, protected lands. Some state lands in the western United States (the so-called “school lands” sections, but not “stewardship” lands) were kept in the developable category because they are in practice sold to generate revenue for state school systems. Also, tribal lands are often considered federal (public), but here we included tribal lands as developable (except for known tribal parks). The portions of blocks that overlapped with public (and other non-developable lands) were deleted to create a modified or refined block. All housing units associated with each block are then assumed to be located in the refined (developable) portion of the blocks. Housing units were apportioned within the refined block using a dasymetric mapping approach described in Table 2-1 below.

3. Road and groundwater well density – The existence of major roads (interstates, state highways, county roads) was used to better allocate the location of housing units within a block. In a previous SERGoM model (v1, v2) housing units were spread evenly throughout the refined blocks. Here, in v3 of SERGoM, housing units are disproportionately weighted to areas of higher likelihood of being developed according to fine-grained land use/cover data from NLCD 2001 (see Table 2-1). Because major road infrastructure is included in the NLCD (actually burned in as values 21, 22, and some 23), road density *per se* was not included. Also, in the western US, where the rural blocks are particularly large, groundwater-well density was included to refine the allocation of units. The analytical hierarchy process (AHP; Saaty 1980) was used to provide an estimate of logical consistency during the development of the weights (the consistency index was 0.035, which is less than the 0.15 threshold, showing that these estimates were logically consistent). Note also that these weights are applied in a relative, not absolute context. That is, the number of units that will be distributed in a given area is specified by the census block and so units are allocated in proportion to the weights found within a given block. This is robust in the face of potential misclassification of land cover types, because all the known housing units will be allocated to a given block, regardless of land cover (but note that the undevelopable – water and public lands – portions of the blocks are excluded).
4. County population projections – Population projections for each county are used to drive the future growth forecasts. Additional housing units needed in each county were computed by determining the number of new housing units needed to meet the needs of the additional population, assuming the same (as in the year 2000) population to housing-unit ratio in each tract, using 2000 U.S. Census of Housing data.
5. Commercial/industrial land use – We also mapped locations with land uses that would typically preclude residential development (increased housing density), especially commercial, industrial, as well as transportation land uses. Using urban/built-up categories from NLCD 2001 (not open space developed), we identified locations (1 ha cells) that had

>25% urban/built-up land cover but very low levels of housing density (i.e. less than suburban). High-density residential areas are otherwise included in the urban/built-up land cover categories. Although some re-development of central business districts (“gentrification”) is occurring, SERGoM works from the operating assumption that these are relatively small portions of the landscape.

Table 2-1. Description of the weights that are applied to NLCD which are used to allocate the block housing units within each block

NLCD Classes	Description	Weight ^a
Open water & perennial ice/snow (11, 12)	No housing units on water or snowfields	0.0
Developed, open space (21)	This is typically either open space (urban parks and greens space) or roads (in rural areas), so very low likelihood of housing units	0.085
Developed, low, medium & high intensity (22, 23, 24)	These cover types are where housing units most likely are located	0.549
Transitional (31, 32, 33)	Includes barren, transitional areas such as cleared or recently cleared areas, but also mines, etc.	0.115
Wildland vegetation (41, 42, 43, 51, 52, 71, 72, 73, 74)	Not likely to have high-density (urban) development in these areas.	0.150
Agricultural (pasture/hay, cultivated) (61, 81, 82)	Will have some housing density, but most housing infrastructure is clustered and near roads.	0.050
Wetlands (90, 91, 92, 93, 94)	Not likely to develop in wetlands (without filling or permits).	0.050

^aNote that the weights are applied to each 30 m cell in the NLCD, then the weights are aggregated up to 100 m resolution by averaging the 30 m weight values.

SERGoM is a demand/allocation/supply model, where the number of new housing units needed for the next decade is computed to meet the demands of the projected population, computed here for each county (although other analytical units are possible). The average growth rate for each state-housing density class combination is computed from the previous to current time step (e.g., 1990 to 2000). These average growth rates are computed using a moving neighborhood for 12 development classes. These classes are formed by overlaying three housing

density classes – urban/suburban, exurban, and rural – with four accessibility classes measured as travel time (minutes one way) from the nearest urban/suburban core along (existing) major roads: 0-10, 10-30, 30-60, and >60 minutes. The resulting combination creates a “surface” of raster values that reflect historical patterns of growth – called allocation weights - and are used to allocate the new housing units for a given time step.

Based on the Census definition of urban areas, urban housing densities are less than 0.1 ha per unit and suburban are 0.1 – 0.68 ha per unit. We defined exurban density as 0.68 – 16.18 ha per unit (to 40 acres) to capture residential land use beyond the urban/suburban fringe that is composed of parcels or lots that are generally too small to be considered productive agricultural land use (though some high-value crops such as orchards are a notable exception). Rural is defined as greater than 16.18 ha per unit where the majority of housing units support agricultural production.

2.2. SRES-SPECIFIC PARAMETERS FOR SERGOM

We used a number of population growth scenarios that are based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) social, economic, and demographic storylines (Nakicenovic and Swart 2000). These scenarios are rendered using a combination of models representing demography. The SRES provide storylines along two major axes, economic vs. environmentally-driven development (A-B) and global vs. regional development (1-2), which make up the four combinations of storylines, A1, A2, B1, and B2. In addition to changes in population that resulted from the various demographic assumptions associated with each SRES-compatible storyline developed for the ICLUS project (USEPA 2009), the spatial location of growth was modified using SERGoM in two ways: household size and travel time (Table 2-2). With SERGoM, household size is expected to reflect demographic changes due to changes in fertility and socioeconomic changes that affect household formation. Travel time from urban “central city” locations is used to help express how the evolution of the urban form might be affected by changing priorities and increases in the cost of transportation.

First, weighting values can be adjusted as a function of distance away (travel time) from urban cores. Urban-area (<5 minutes) weights can be lowered by a given percentage to reflect a carrying capacity or saturation of an area, specified by zoning perhaps; or raised to reflect increased desire for urban living (lofts, gentrification, etc.). Exurban-area weights (~30-60 minutes) can be lowered to reflect assumptions of lower rates of development due to increased fuel prices or can be used as a surrogate for lower land availability because of increased conservation purchases (or easements). Weights can also be raised for exurban areas to reflect increased “urban flight” of baby-boomer retirees and rural amenities. This weighting surface is

re-computed at each time step. We modified the weights of travel times for the B1 and B2 storylines to model a “compact” growth scenario (see Table 2-2). Given the environmental orientation of the B1 and B2 storylines, we assumed that growth patterns in these scenarios would place a greater emphasis on promoting denser growth patterns closer to existing urban centers. The baseline scenario uses the midline US Census Bureau projection of population growth and assumes no other changes from business-as-usual development patterns.

Table 2-2. Summary of Adjustments to SERGoM v3 for SRES scenarios.

Scenario	SERGoM parameters		
	<i>Household size</i>	<i>Travel time (minutes)</i> <5; 10; 20; 30; 45; 45	<i>Travel time consequences for urban growth form</i>
A1	Smaller (-15%)	75; 75; 85; 90; 95; 100	No change
B1	Smaller (-15%)	90; 95; 85; 90; 95; 100	Slightly compact
A2	Larger (+15%)	75; 75; 85; 90; 95; 100	No change
B2	No change	90; 95; 85; 90; 95; 100	Slightly compact
Baseline	No change	75; 75; 85; 90; 95; 100	No change

A second type of modification is changing assumptions about households, particularly household size (roughly family size), defined as the number of people living in a single housing unit. Currently this ratio (population per housing unit) is static and is computed at the tract level from the 2000 U.S. Census data. We modified this ratio to reflect assumptions in the SRES scenarios to adjust for assumed changes in demographic characteristics. For example, SRES A1 and B1 assume smaller household sizes (a reduction by 15% throughout the future decades), whereas scenarios B2 and baseline are not changed and A2 assumes a 15% increase in household size (Jiang and O’Neill, 2007). The changes in household size correspond to changes in fertility rates that are assumed under the different storylines. Under A1 and B1, where fertility is lowest, smaller average household sizes are also expected. Conversely, A2 has the highest fertility rates, so an increase in household sizes is expected. In B2, which uses the medium fertility rates, household sizes are not changed. Household size remains unchanged in the baseline scenario.

Modifying urban form and household size requires several parameter changes in SERGoM. To model the “compact” growth scenarios (B1 and B2), SERGoM was run with modifications to the spatial allocation of new housing units as a function of travel time from urban cores. Urban

cores were defined as a contiguous grouping of urban/suburban cells at least 128 ha in size. The changes in household sizes for each scenario translate into the following parameter changes in SERGoM: each census tract was modified by 0.85 for A1 and B1 scenarios, and by 1.15 for A2; B2 and baseline scenarios are unchanged.

3. TOOLS

3.1. SETTING UP THE ICLUS TOOLS

This section describes the specific steps required to use the ICLUS toolset in ArcGIS.

Extract the **ICLUS_v1.3.zip** file to a location other than your desktop. **Avoid path names that include special characters (e.g. parentheses, quotation marks) or spaces.** You will see five folders titled: “base”, “documentation”, “population”, “output”, and “software”. All underlying datasets needed to run the ICLUS tools must be located in the “.../ICLUS_v1.3/base” directory.

Start either ArcMap or ArcCatalog, right-click in the ArcToolbox panel, and select “Add Toolbox”. Navigate to the “.../ICLUS_v1.3/software” folder and add the red toolbox named “ICLUS v1.3” (Figure 3-1).

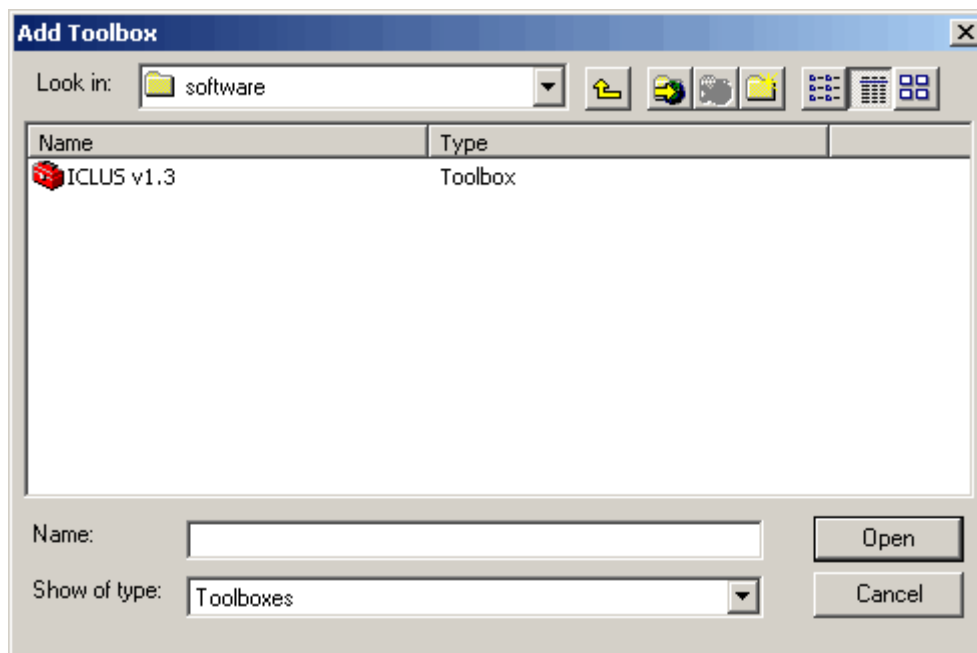


Figure 3-1: Loading the ICLUS Toolbox into ArcGIS

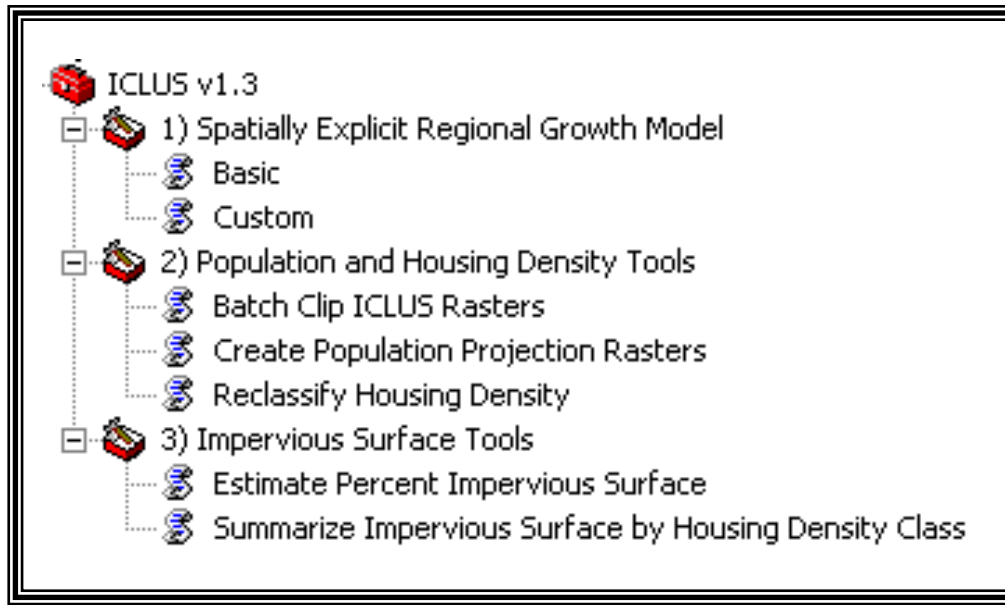


Figure 3-2: The Expanded ICLUS Tools

The tools are split into three general groupings. The first toolset contains two versions of the **Spatially Explicit Regional Growth Model (SERGoM)** (Figure 3-2). The **Basic** version of SERGoM will create housing density rasters for a user-specified time period under user-specified ICLUS scenarios. Alternatively, a **Customized** SERGoM model run can be executed for a single ICLUS scenario using user-specified parameters (i.e. travel-time weights, household size). The **Population and Housing Density** and **Impervious Surface** toolsets provide other functions for creating and managing ICLUS datasets. Some fields in the SERGoM-model tools will automatically populate with default values. All fields with a green dot next to them are required.

The following sections provide a description of each tool screen.

3.2. SERGOM: THE SPATIALLY EXPLICIT REGIONAL GROWTH MODEL

There are two version of the SERGoM-model user interface included in this toolset. Besides the user interface, the specifics of the model executed by each tool are identical. The “Basic” version only requires the selection of a time period, ICLUS population scenario(s), and output options (Figure 3-3). This version of the model will run with the default SERGoM parameters found in Table 2-2. The

“Custom” version allows users to specify travel time weights and a household size adjustment; however, only one ICLUS population scenario may be selected at a time.

3.2.1 BASIC SERGOM

This is a simplified interface for SERGoM that will create nationwide housing density data (100 meter resolution) for a given set of ICLUS growth scenarios over a specified time period (Figure 3-3). Note that running this tool for all years and all scenarios typically requires 100 hours of run time and generates 50+ GB of output. Model output will be placed in the “.../ICLUS_v1.3/output” directory.

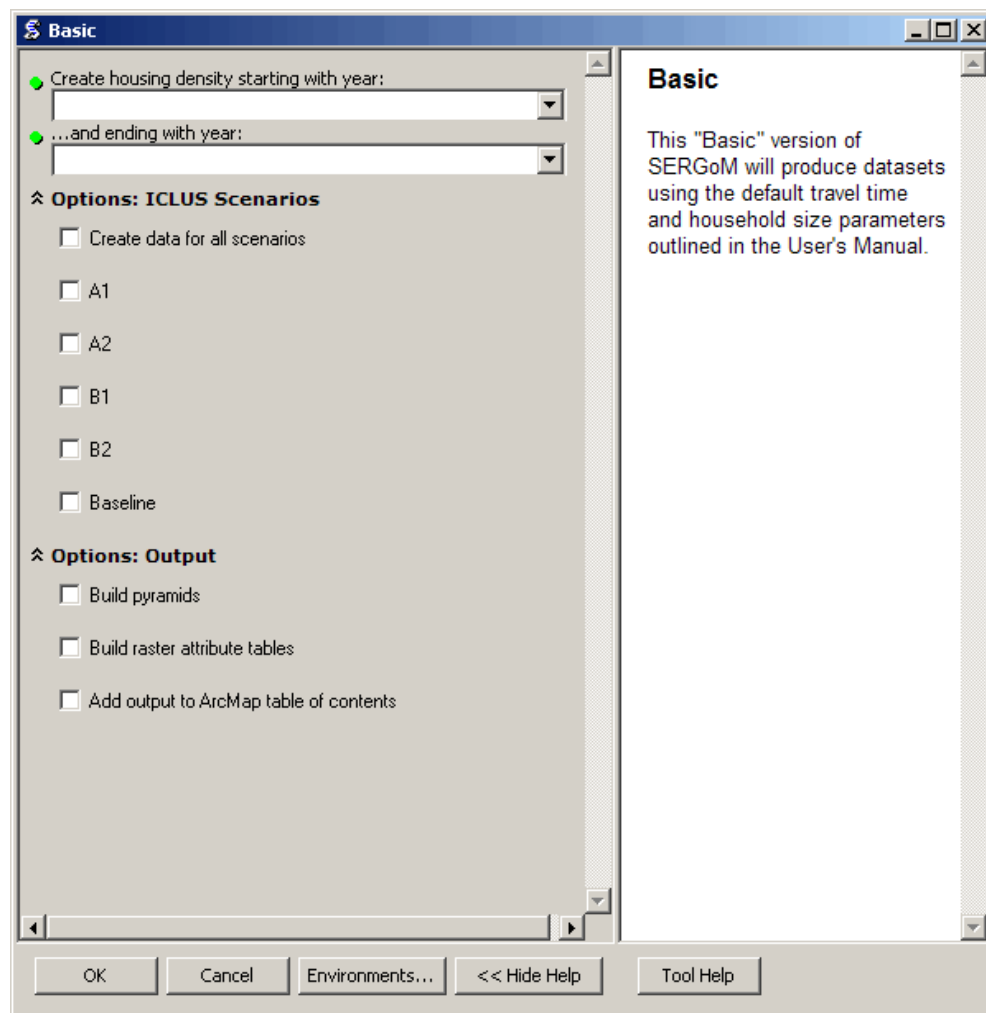


Figure 3-3: Basic SERGoM User Interface

3.2.2 CUSTOMIZED SERGoM

The “Custom” version of SERGoM will accept changes to the default travel time weighting scheme and household size adjustments outlined on page 8 (Figure 3-4). Model output will be placed in the “.../ICLUS_v1.3/output” directory.

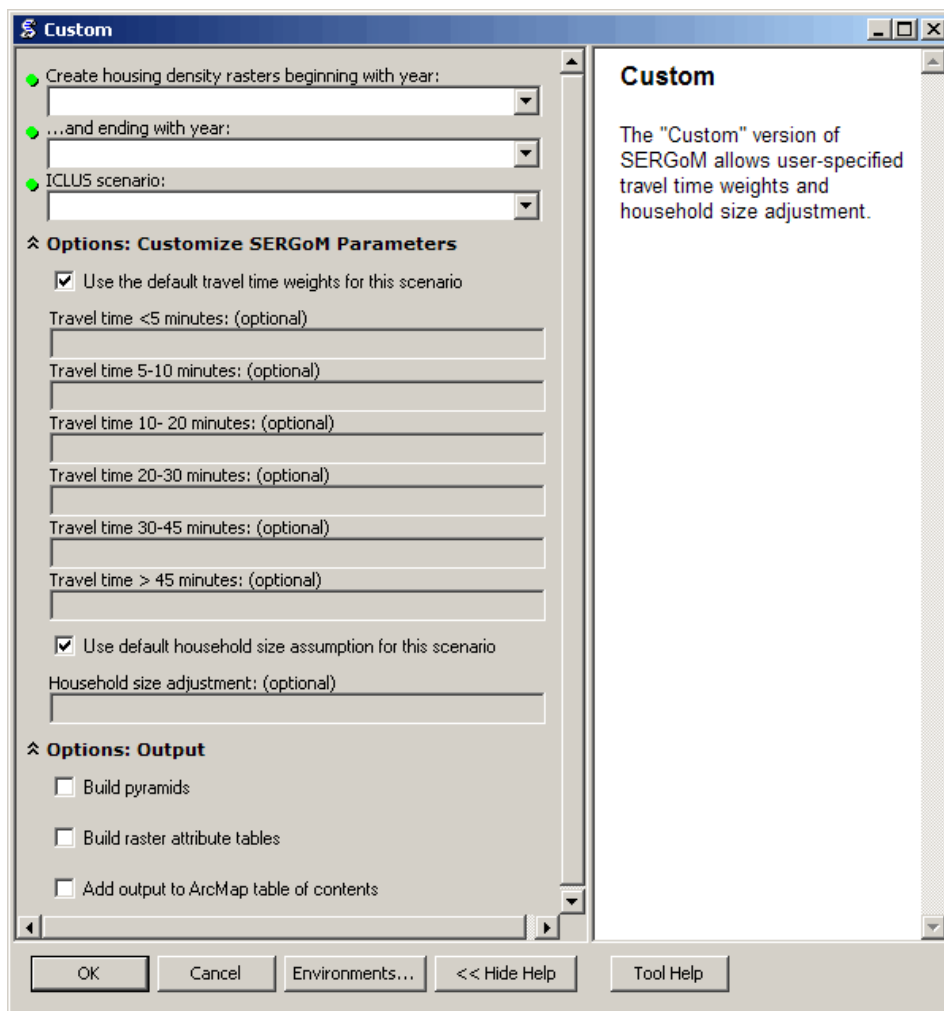


Figure 3-4: Custom SERGoM User Interface

3.3. BATCH CLIP ICLUS RASTERS

The SERGoM model will only create nationwide datasets; these datasets are fairly large in terms of file size. The User can apply the Batch Clip tool to extract data for an area of interest (Figure 3-5). This is especially useful when only certain parts of the country are of interest, rather than the whole coterminous US. The clip mask can be any polygonal boundary that the

User wants to “cut out” and save from the main input rasters. Users select where the finished products will be stored in the Output Folder choice. Those data may then be used as input for other ICLUS tools, significantly reducing processing times. **Projection for ‘Clip Mask’ polygon must be: USA Contiguous Albers Equal Area Conic USGS (projection file located in “base” folder).**

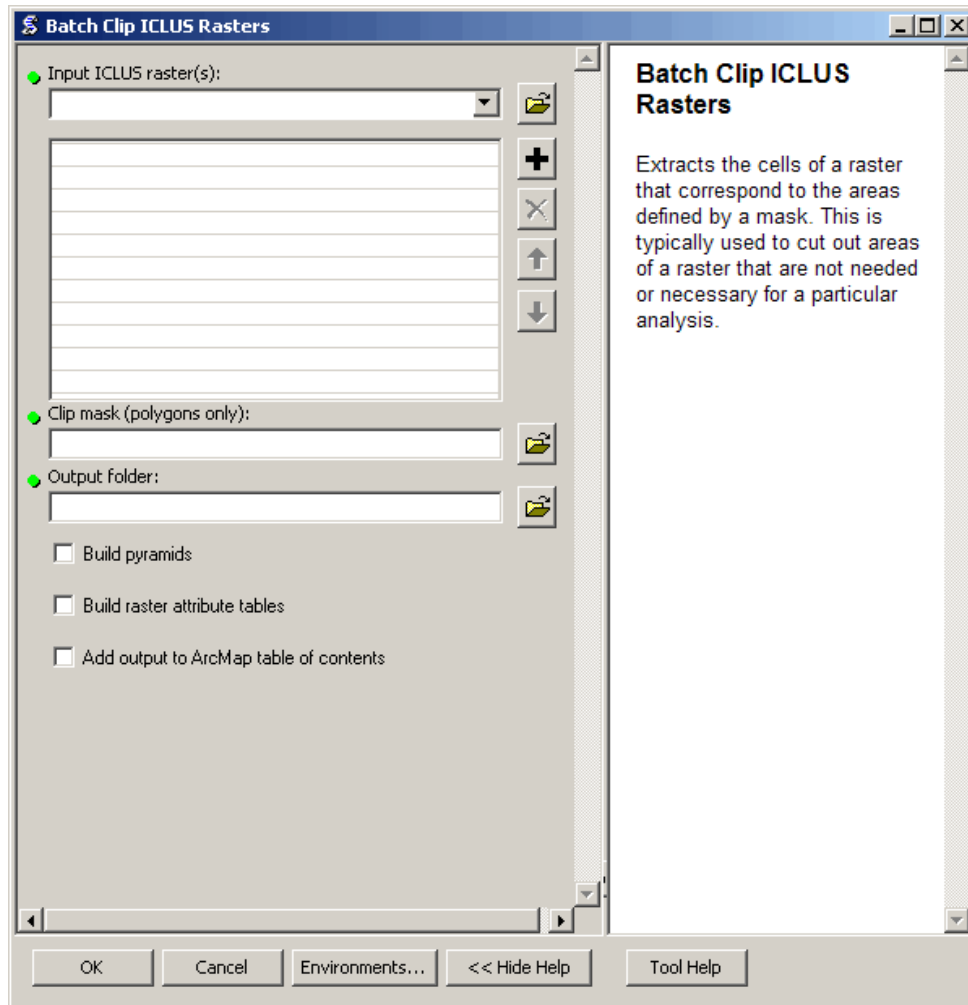


Figure 3-5: Opening Screen for the Batch Clip ICLUS Rasters Tool

3.4. CREATE POPULATION PROJECTION RASTERS

This tool creates population projection rasters from “cofips_upp” shapefile located in the “base” folder (Figure 3-6). These rasters are used by the SERGoM model, but are also appropriate for analyses requiring county-level populations. The various ICLUS scenarios can be selected using the pull-down menu next to the field. Only valid choices are accepted. These

rasters can also be created “on the fly” by simply running the SERGoM tool. Population rasters will automatically be placed in the “population” folder.

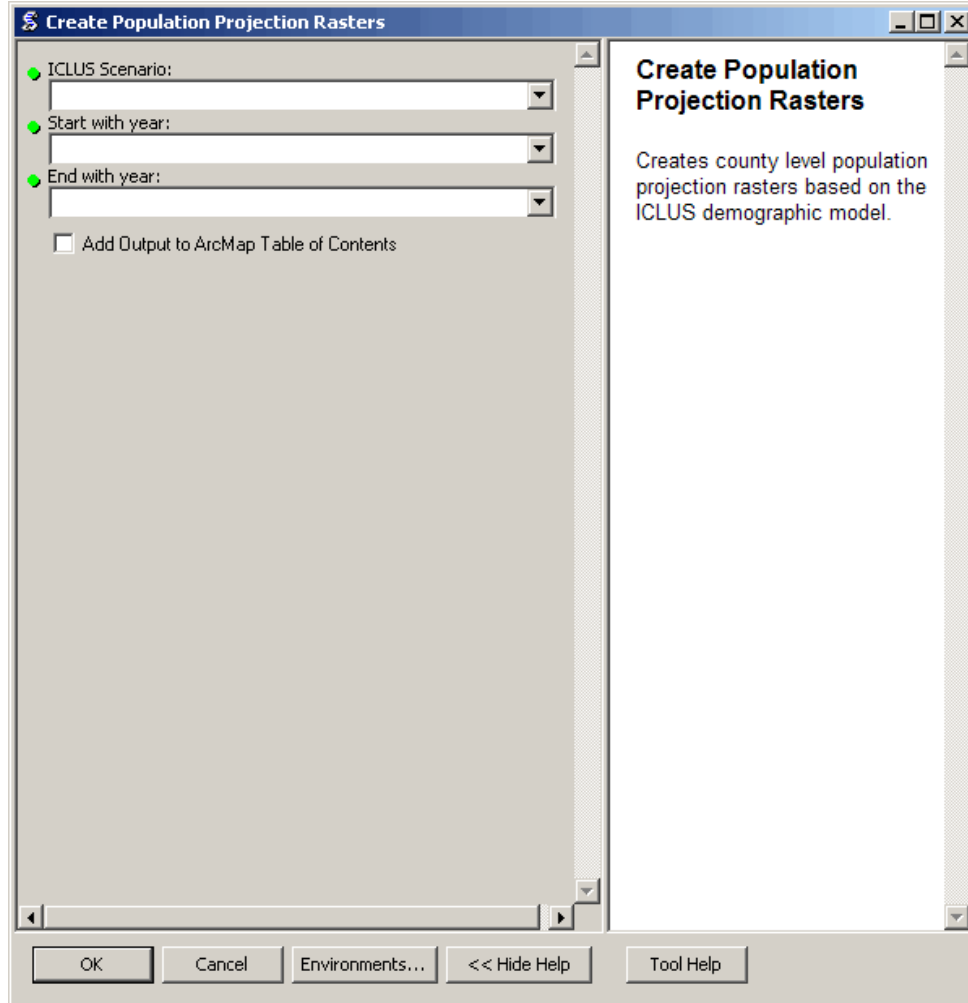


Figure 3-6: Opening Screen for Create Population Projection Rasters Tool

3.5. RECLASSIFY HOUSING DENSITY TO CLASSES

This tool reclassifies raw block housing density values into density classes (Figure 3-7). Commercial land pixels, which are static in the ICLUS v1.3 model, may also be incorporated into the output of this tool. **There are two classification schemes available; please check the within-tool help screens for details.**

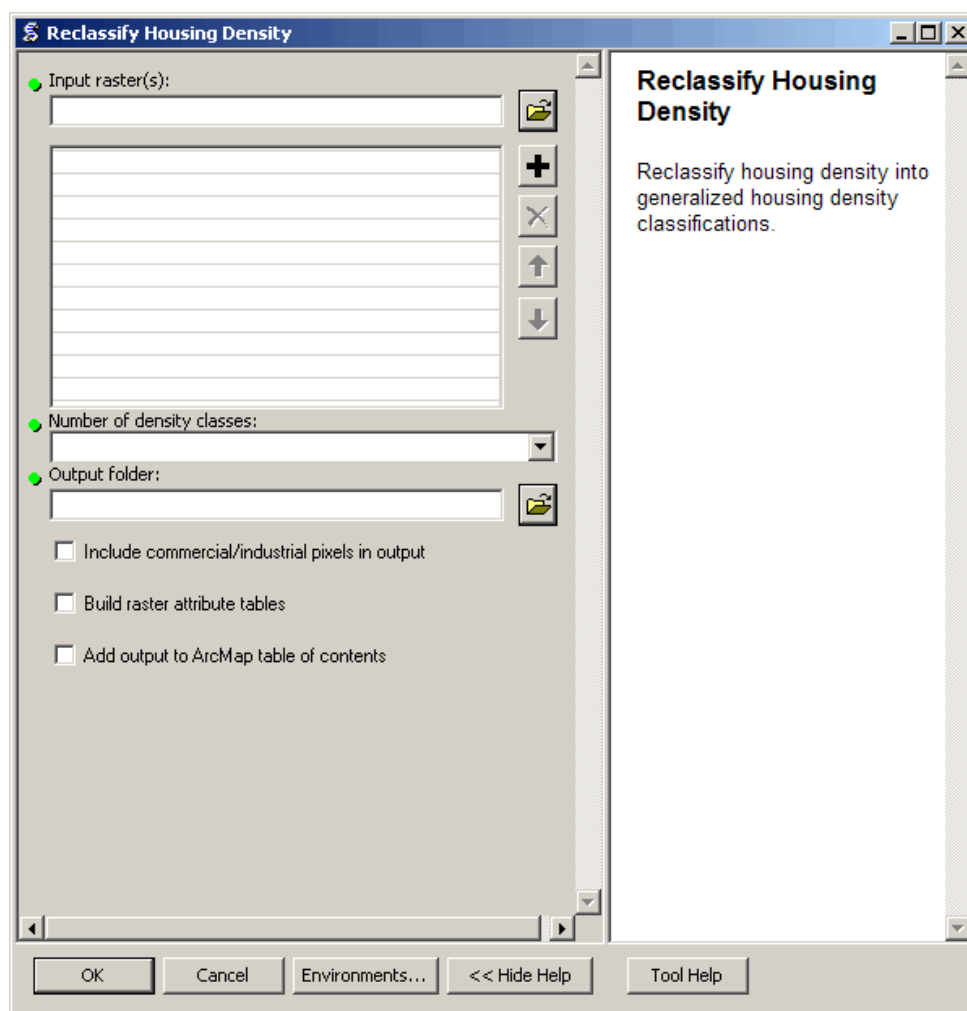


Figure 3-7: Opening Screen for the Reclassify Housing Density Tool

3.6. ESTIMATE PERCENT IMPERVIOUS SURFACE

This tool reclassifies block housing density values into estimated percent impervious categories (Figure 3-8). A Categorical Regression Tree model was used to develop a regression equation that describes the relationship between the Percent Urban Imperviousness (PUI) dataset produced by the MRLC Consortium and housing density (see Appendix C in USEPA 2009 for more details). This relationship was then converted into a set of conditional statements which form the basis for this tool.

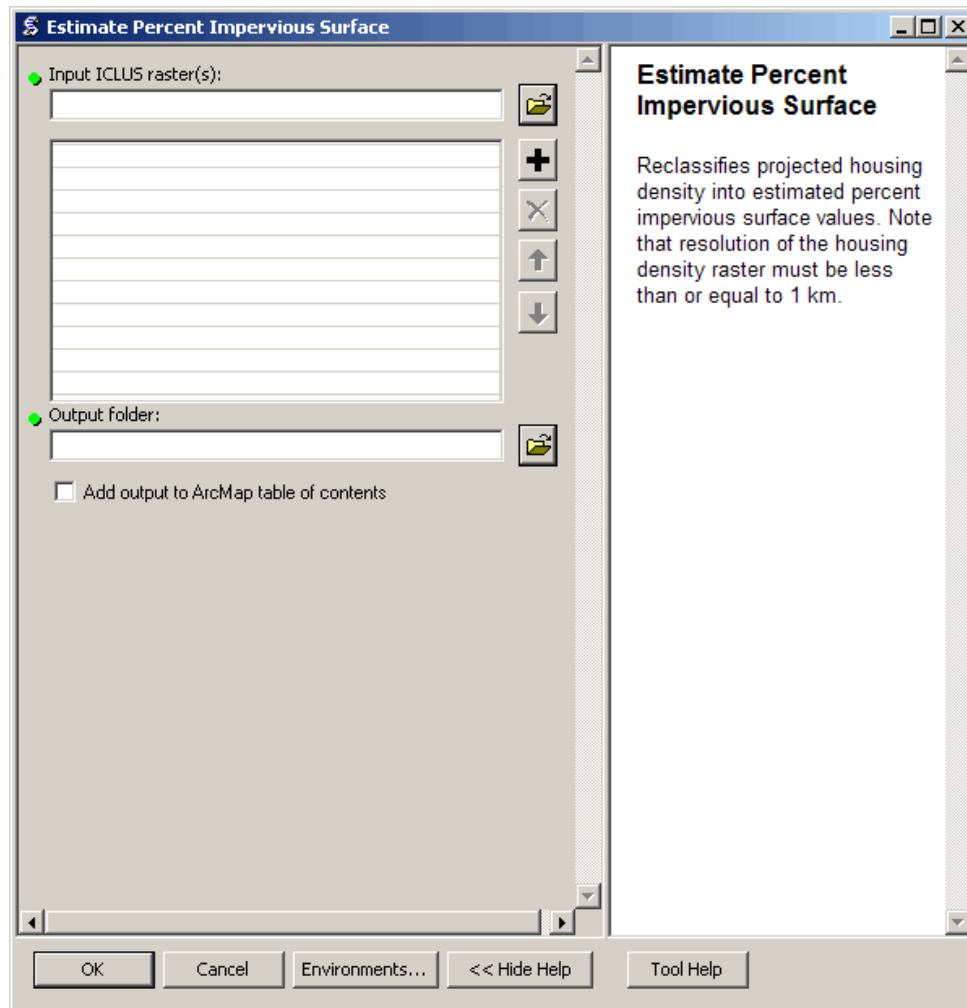


Figure 3-8: Opening Screen for the Estimate Percent Impervious Surface Tool

3.7. SUMMARIZE IMPERVIOUS SURFACE BY HOUSING DENSITY CLASS

This tool uses housing density classes to summarize estimated percent impervious surface (Figure 3-9). This tool combines the “Reclassify Housing Density” and “Estimate Percent Impervious Surface” tools to calculate the distribution of impervious surface among housing density classes.

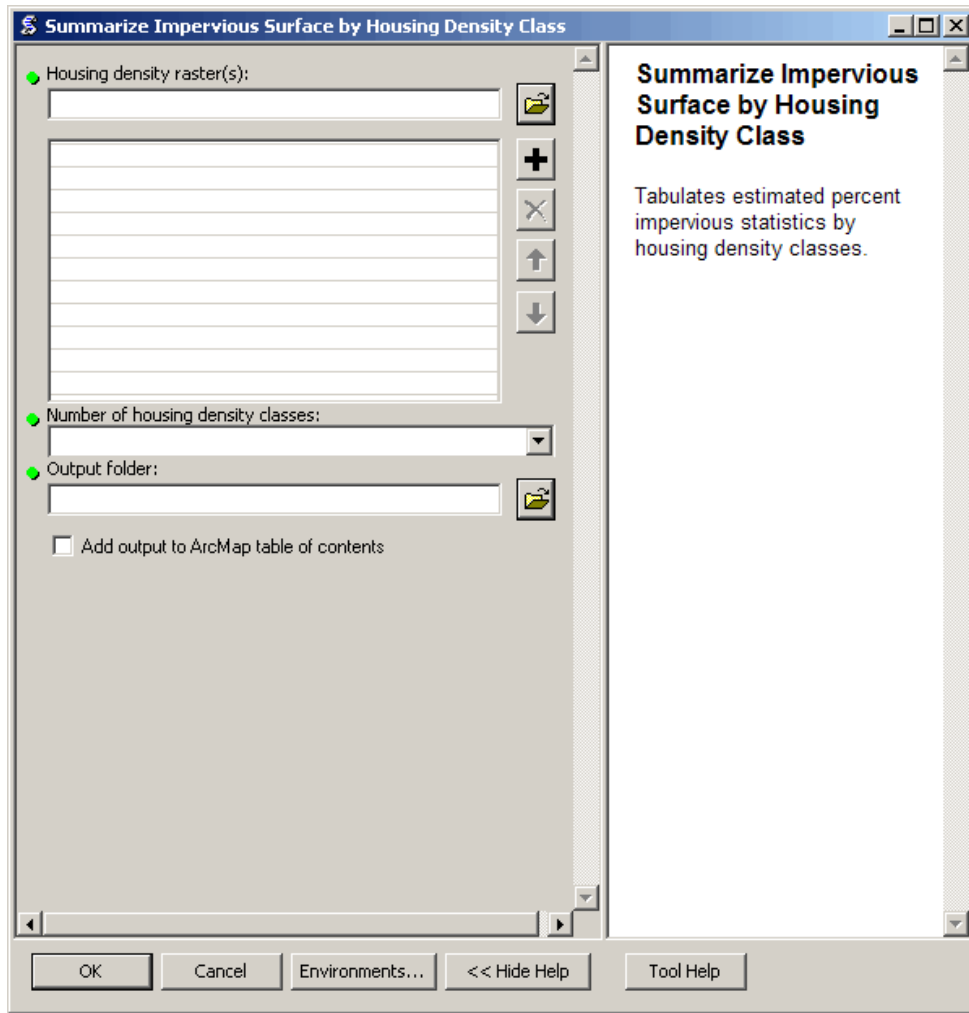


Figure 3-9: Opening Screen for the Summarize Impervious Surface by Housing Density Class Tool

4. REFERENCES

- Jiang, L; O'Neill, BC. (2007) Impacts of demographic trends on US household size and structure. *Population and Development Review* 33(3): 567-591.
- Nakicenovic, N; Swart, R, eds. (2000) *Special report on emissions scenarios* Cambridge, UK: Cambridge University press.
- Saaty, A. (1980) *The Analytic Hierarchy Process: planning, priority setting, resource allocation*, McGraw-Hill.
- Stein, SM; McRoberts, RE; Alig, R; et al. (2005) *Forests on the Edge: housing development on America's private forests*. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station PNW-GTR-636. May 2005. <Online> URL: <http://www.fs.fed.us/projects/fote/reports/fote-6-9-05.pdf>
- Stein, SM; Alig, R; White, EM; et al. (2007) *National Forests on the Edge: development pressures on America's National Forest System*. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, PNW-GTR-728. August 2007.
- Theobald, DM. (2001) Land use dynamics beyond the American urban fringe. *Geographical Review* 91(3):544-564.
- Theobald, DM. (2003) Targeting conservation action through assessment of protection and exurban threats. *Conservation Biology* 17(6):1624-1637.
- Theobald, DM. (2005) Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecology and Society* 10(1): 32. [online] URL: <http://www.ecologyandsociety.org/vol10/iss1/art32/>.
- U.S. EPA (Environmental Protection Agency). (2009) *Land-Use Scenarios: National-Scale Housing-Density Scenarios Consistent with Climate Change Storylines (Final Report)*. U.S. Environmental Protection Agency, Washington, DC; EPA/600/R-08/076F. Available from the National Technical Information Service, Springfield, VA, and online at <http://www.epa.gov/ncea>.