CLEARING HOUSE Spatial Impact Assessment and Classification Tool (SIAC)
Version 0.4

CLEARING HOUSE Spatial Impact Assessment and Classification (SIAC) Tool

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SIAC License

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Objectives

The SIAC tool is developed by the CLEARING HOUSE project to assist in assessing conditions of urban forest as nature-based solutions (UF-NBS) and estimate benefits provided by UF-NBS at a local level. For example, SIAC is intended to support addressing the following challenges:

- Modelling/assessment of tree cover, thereby contributing to IUCN’s urban nature index theme 3.1: Identification of (trends in) vegetation cover (IUCN, 2023).

- Assessment of tree species richness and diversity, thereby contributing to IUCN’s urban nature index theme 4.2: Identification of (trends in) plant species diversity (IUCN, 2023).

- Modelling/assessment of tree cover connectivity, thereby contributing to IUCN’s urban nature index theme 3.5: Identification of (trends in) connectivity (IUCN, 2023). Moreover, through an identification of articulation points and bridges, SIAC may support decision-making on maintaining connectivity through identifying nodes and links (edges) important for overall connectivity.

- Rapid, indicator-based assessment of tree cover benefits. This includes, for example, indicators on carbon storage and carbon sequestration, or on the regulation of air quality through the removal of pollutants. Thereby, SIAC may contribute to IUCN’s urban nature index theme 5.3: Human health (IUCN, 2023).

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Requirements and installation

Requirements and dependencies

SIAC is a toolkit that contains a number of tools for the assessment and classification of Urban Forest entities. It is written as a plugin for the QGIS open-source desktop GIS. More-specific dependencies on running SIAC in QGIS with respect to software versions are as follows:

- QGIS (3.28.2) 64bit
- Python (3.9.X) as bundled with QGIS

Moreover, for the operation of SIAC, the following packages are required to be installed for QGIS, with the minimum versions as indicated in the following table. Please make sure that each of these dependencies is installed with at least the version stated before continuing to install the plugin itself.

Figure 1. SIAC dependencies.

Package name	Minimum version
geopandas	0.13.0
matplotlib	3.5.1
momepy	0.6.0
networkx	3.1
pandas	1.1.3
scikit-learn	1.3.0
seaborn	0.12.2
shapely	2.0.1
statsmodels	0.14.0
xlsxwriter	3.1.2

The installation of packages is described in the following section.

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Installation and setup

QGIS

Make sure that minimum software version of QGIS (3.28.2) is met. Install a corresponding version if this is not being the case. QGIS can be downloaded from the following website: https://qgis.org/en/site/forusers/download.html.

SIAC dependencies

Install required python packages/SIAC dependencies. To do so, open the environment to conduct the installation of dependencies. This corresponds to the OSGeo4W shell that is provided with QGIS, therefore:

Open the OSGeo4W shell, e.g., from the start menu/QGIS

In the OSGeo4W shell, check the packages/dependencies that are already installed. Issue the following command:

```
pip list
```

In the shell, a list of installed packages will be printed, including their version number. Check this list against required SIAC dependencies to identify packages that require installation if not present. To install a missing dependency, issue the following command:

`pip install <packagename>`, e.g., to install *momepy*, enter
`pip install momepy`

Alternatively, if a package is already installed, but the version number is lower than indicated in the table of dependencies, an upgrade of the package is needed. To do so, issue the following command:

`pip install --upgrade <packagename>`, e.g., to upgrade networx enter
`pip install --upgrade networkx`

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Plugin

At this time, SIAC is not available via the QGIS plugin repository, therefore, it needs to be installed by hand from the provided zip archive. To install the plugin, follow the steps outlined below:

- Start QGIS.
- Choose to manage and install extensions from the extensions menu, then choose to install from a ZIP file.
- Point to the provided ZIP file, and install.

SIAC should now be installed, activated, and loaded correctly.

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Licenses, Attributions and Acknowledgements

This tool uses the NetworkX library (Hagberg et al., 2008). NetworkX is distributed with the 3-clause BSD license.

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This tool uses the momepy library (Fleischmann, 2019). Momepy is distributed under the 3-clause BSD license.

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This tool uses the xlsxwriter library. XlsxWriter is released under a BSD 2-Clause license.

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This tool uses the geopandas library (Jordahl et al., 2020). Geopandas is distributed under the 3-clause BSD license.

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Operating SIAC

Introduction to the SIAC plugin window

Overview

SIAC provides a QT-based user with its own menu and status bar etc. All functions of SIAC are accessible through this plugin window. It can be opened by clicking on the button in the QGIS toolbar, or by default, pressing CTRL+F9. The plugin window is shown in the Figure 2.

Central to the plugin window is the tool log, that displays assessment results and messages to the user. Moreover, the plugin window features various dockable windows, including a window to manage data sources and one to set parameters. These dockable windows can be dragged to different positions of the plugin window (e.g., docked to the left/right/top/bottom, stacked at a dock position) or undocked entirely from the plugin window as a floating window for easier accessibility. The visibility of windows may be toggled in the View menu.

Menu and toolbar provide access to the various tool functionalities.

The status bar at the bottom of the plugin window provides several indications: An activity indicator and status messages (left); information regarding user-specified/available data sources (active layer, external data) (right); and model’s coordinate reference system (CRS).

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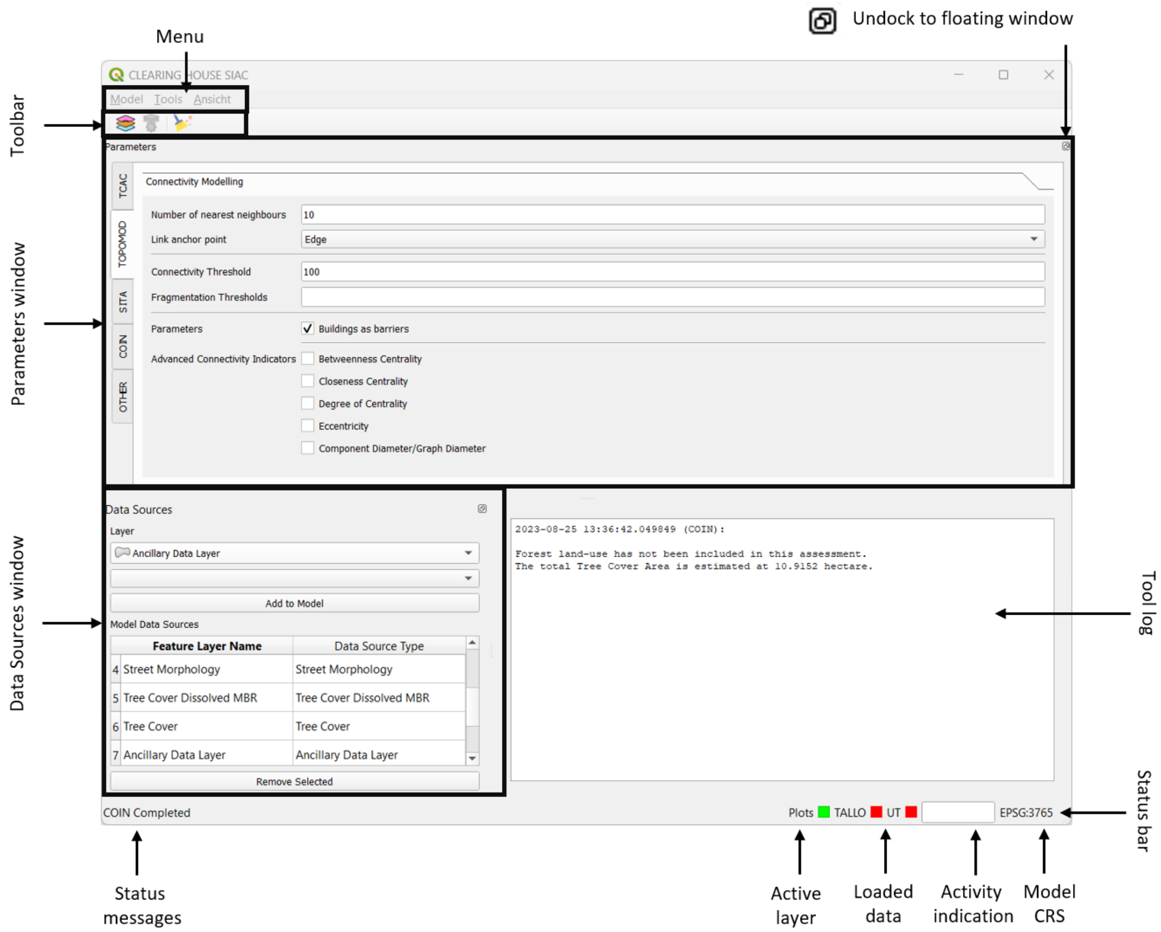

Figure 2. SIAC plugin window with “Data Sources” tab shown.

The Data Sources window

The Data Sources window is shown in Figure 3. It lists all data sources (layers) included in the SIAC model, and allows adding or removing data sources to/from the model. When right-clicking on a layer from the list of included data sources, a context menu is provided with further available actions.

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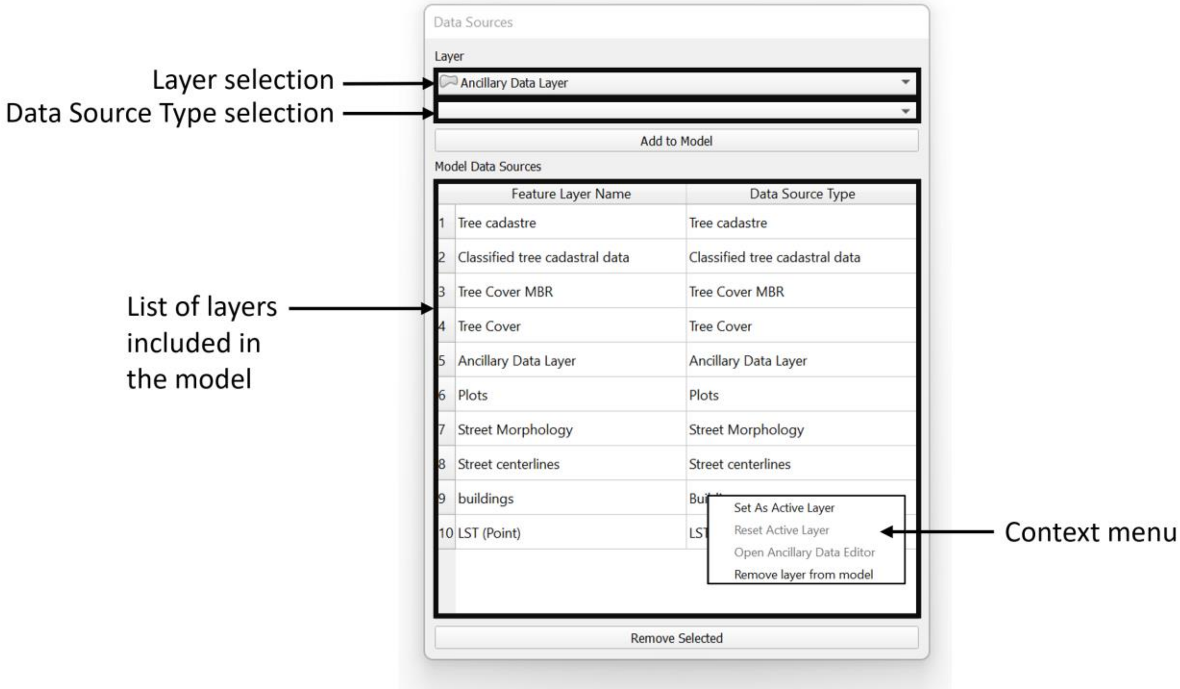

Figure 3. Data Sources window.

The Parameters window

The Parameters window allows the user to define various parameters used in or across the various modules (tools) provided by SIAC.

Parameters are organized into categories, that are broadly aligned with individual SIAC tool modules. Within each category, parameters are then grouped, with each group broadly aligned to functions provided by the tool in question. In so-doing, relevant parameters are typically displayed side-by-side to facilitate operation of SIAC. The various parameters are described in detail for each module later in this manual.

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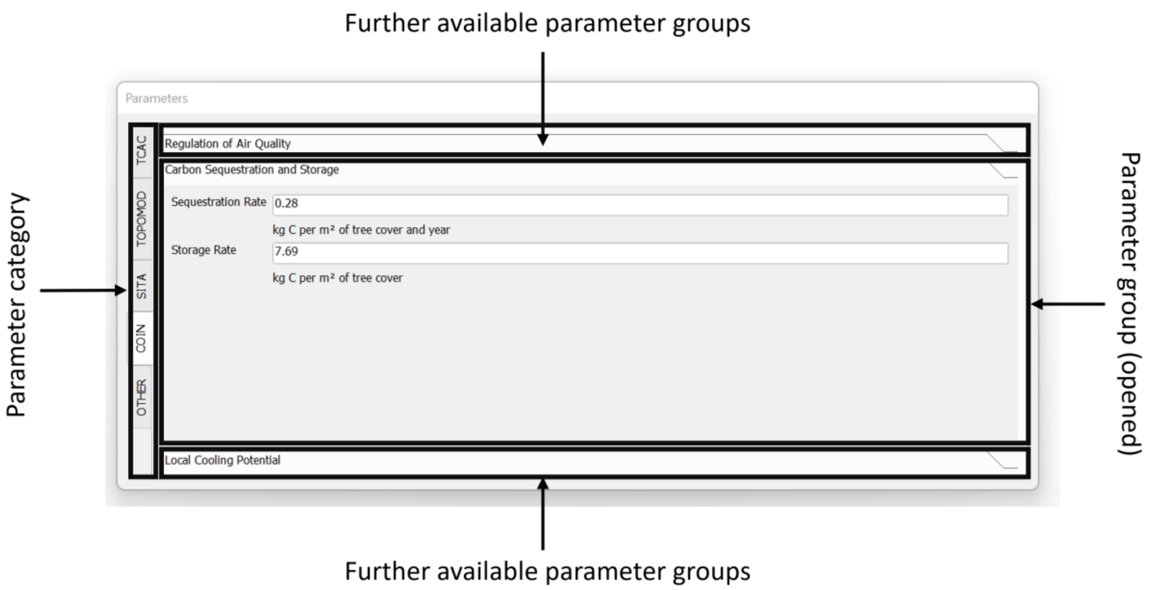

Figure 4. The Parameters window.

Managing SIAC model data

SIAC model data broadly refers to the data sources (layers) included in a SIAC model. In this regard, SIAC handles various types of spatial data (layers), with data sources typically falling into one of two distinct categories: (i) mandatory input layers, that are required by the various tools as described below; or (ii) ancillary layers, that may be included in a model to convey additional spatial data with semantic meaning to SIAC tools. The use of ancillary data layers is optional. They are supported by a subset of tools, e.g., SITA.

> At a general level, for each input layer type, only a single layer per type is supported by SIAC. However, for layers of type Ancillary Data Layer, multiple layers of this type may be added to the model.

Adding layers to a SIAC model

Adding input layers and ancillary data layers is managed in the Data Sources window. To add data sources to the model, it is initially suggested to first load all respective data as map layers into QGIS. Then, in the Data Sources window, conduct the following steps for each input data source or ancillary data source as outlined below.

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(1) Select a feature layer from the *Layer selection* combo box.

(2) Select the appropriate data source type from the *Data Source Type selection* combo box. This data source type conveys a semantic meaning to SIAC, i.e., it denotes the content of the layer in question to the tool. For ancillary layers, select Ancillary Data Layer as type.

(3) Click the “Add to Model” button. The layer will be added to the SIAC model, and listed accordingly in the list of included layers with its layer name and data source type.

Repeat these steps as needed, for each layer that shall be included in the model. Refer to the documentation to read on input data required by the various SIAC tools.

Outputs of the various SIAC tools are typically added automatically to the QGIS map and to the SIAC model upon tool completion.

When opening the plugin for the first time, the coordinate reference system (CRS) set for the QGIS map frame will automatically be set for the SIAC model. The current model CRS is shown in the plugin window’s status bar. When adding a layer to the SIAC model, the layer’s CRS is checked against the model’s CRS, and an on-the-fly projection is conducted on the layer if both CRS do not match. Please note that this process may take some minutes particularly for larger layers.

To facilitate adding layers to the SIAC model, the tool provides a matching function that attempts to automatically add layers from the QGIS map frame into the model based on its layer name as shown in the QGIS Layer window. More specifically, a layer is added to the model if its layer name is verbatim to a data source type; e.g., a layer named “Tree Cadastre” is automatically added to the model as a layer of “Tree Cadastre” data source type. Please refer to the description of input data sources below for more details on required layers/data source types per tool module.

The layer matching function can be invoked from the Model menu by clicking “Resolve data sources”, or using the CTRL+SHIFT+R keyboard shortcut.

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Removing layers from a SIAC model

There are various options to remove a layer from a SIAC model:

> Select the layer to be removed from the list of included layers in the Data Sources window, then click the button “Remove Selected” located under the list of included layers.

Alternatively,

> Open the context menu by right-clicking on the layer to be removed in the list of included layers in the Data Sources window, and remove the layer by selecting the appropriate option from the context menu.

Alternatively,

> To remote all layers from the SIAC model, thus clearing all tool data, select “Remove All” from the File menu.

Managing the active layer

Various SIAC tool modules, e.g., SITA and COIN, may operate on a so-called active layer that serves as input layer to these tools. Consequently, running such SIAC tools requires the active layer to be set. To do so:

> Double-click on a layer in the list of layers included in the SIAC model in the Data Sources window.

Alternatively,

> Right-click on a layer in the list of included layers in the Data Sources window and select the appropriate option from the context menu.

You may also de-select (reset) the active layer. To do so, follow these steps:

> Right-click in list of layers included in the model to open the context menu, and choose the appropriate option from the context menu.

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Whenever a layer is set as active layer, the corresponding layer name is shown as confirmation in the plugin window status bar. Additionally, the corresponding indicator will show in green. If no active layer is set, “No active layer” is shown in the status bar, with the corresponding indicator shown in red.

Please note that at this time, only polygon feature layers may be used as active layer.

Managing ancillary layers

Ancillary layers provide spatial data with additional semantic meaning to the SIAC tool. For example, ancillary layers may represent features of distinct land-use such as urban green spaces, or may represent features with distinct meaning, e.g., flowerbeds or play equipment. This meaning is referred to as entities, or entity type. In this regard, e.g., in the case of land-use, a land-use layer added to the SIAC model as ancillary data may therefore provide information on multiple entity types related to land-uses at once, e.g., urban green spaces, waterbodies, forest.

Entities/entity types may be defined for ancillary data at two distinct levels:

- At the data source level: Semantic meaning may be defined for an ancillary layer as a whole, i.e., all features in the layer are considered to represent a given semantic entity (this is referred to as “Entities are the layer features” mapping or by-layer mapping);

- At the attribute level: Semantic meaning may be defined for an ancillary layer based at the attribute level, i.e., semantic entities are defined based on attribute values for a specified field in the attribute table (this is referred to as “Entities from attribute values” mapping or by-attribute mapping).

To define the semantic meaning of an ancillary data layer, first open the ancillary data editor (Figure 5).

Open the Ancillary Data Editor Window. To do so, right-click on a given ancillary layer in the list of layers included in the model in the Data Sources window, then select the appropriate option from the context menu.

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Then, in the ancillary data editor, proceed as follows to define either a by-attribute mapping or a by-layer mapping. To define a by-attribute mapping:

(1) Select the appropriate mapping type from the *mapping type* combo box in the ancillary data editor.

(2) From the *Attribute table field selectio*n combo box, select the field from the ancillary layer's attribute table that you wish to use for the mapping. Values from this field are subsequently mapped to specific entity types.

(3) From the *Entity type* combo box, select an entity type you wish to include in the SIAC model.

(4) From the *Attribute value* combo box, select a feature attribute value that represents the chosen entity type. For example, for a land-use layer, features with a value of "urban green areas" in the chosen attribute field may indicate features of the entity type "URBAN GREEN SPACE".

(5) Click the "Add" button to add the attribute value-entity type combination to by-attribute mapping. The respective combination of values/types will be shown in the list of defined combinations.

Repeat steps steps for all attribute value-entity type combinations, as needed. To remove an attribute value-entity type combination, select it from the list of combinations, and click the "Remove" button. Close the ancillary data editor window when done.

To define a by-layer mapping:

(1) Select the appropriate mapping type from the *mapping type* combo box in the ancillary data editor.

(2) Select the entity type that all features in the ancillary layer represent.

Close the ancillary data editor window when done.

Ancillary layers and entities are managed internally by the SIAC tool. I.e., each SIAC tool processes user-defined entity types internally as needed, and as supported by the tool.

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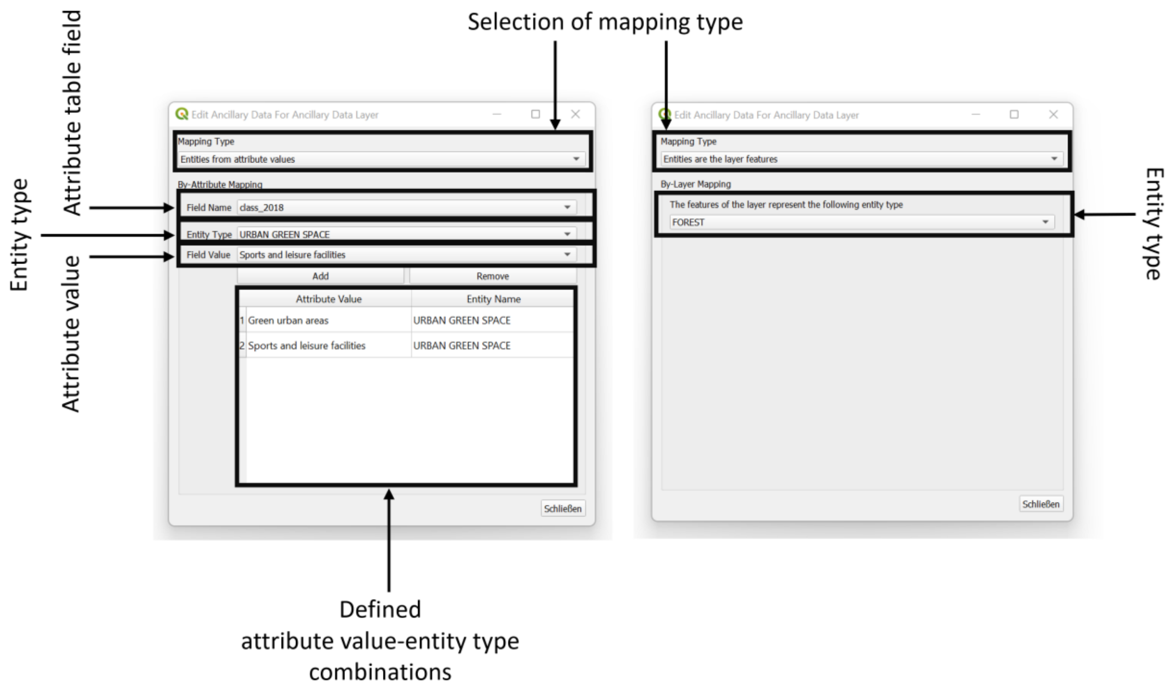

Figure 5. Ancillary Data Editor window. By-attribute mapping (left) and by-layer mapping (right).

Managing external data

SIAC allows importing of external databases for use in selected tool functions. At this time, the following external databases are supported: TALLO database (Jucker et al., 2022); and Urban Tree Database (McPherson et al., 2016). Either database may be imported from the Model/Import menu.

To import a database, choose the corresponding database type from the Model/Import menu. Then point to the respective database file, that needs to be provided in comma-separated values (CSV) format.

When a respective database is imported into the tool, the corresponding indicator in the status bar will show in green; otherwise, in red.

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SIAC tool modules

Overview

SIAC comprises various tools (modules) for dedicated purposes. All tools/modules can be invoked from the Tools menu of the SIAC plugin window. The following table outlines the purposes of each tool module briefly.

Table 1. Overview of included tool modules.

Module	Purpose
TCAC (Tree Configuration Assessment and Classification)	The TCAC module is primarily concerned with the modelling of tree cover, and the assessment of the spatial-morphological configuration of tree features and of tree species richness and diversity. Further functions provided by the module include, e.g., tools to derive tree traits from supported tree databases.
TOPOMOD (Tools for the modelling of spatial relationships and topology)	The TOPOMOD module allows assessing spatial-topological relationships of trees or tree cover with anthropogenic urban features such as streets or buildings, and furthermore implements an assessment of connectivity and fragmentation based on tree-based entities.
SITA (Site assessment)	The SITA module is intended to derive traits for user-defined spatial units of analysis, i.e., patches/plots delineated by a polygon features.
COIN (Computation of Indicators)	The COIN module seeks to estimate indicators on urban forest conditions, e.g., tree cover or forest cover, and furthermore seeks to assess benefits, i.e., ecosystem services provided by the urban forest such as the regulation of air quality.
Pre-Processing	The Pre-Processing module includes functions for the generation of spatial urban-morphological data if no such data is available, including, e.g., the modelling of street morphology (ground area) and of plots.

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Applications of SIAC tool modules

In the following, the application of the various SIAC tool modules is outlined. To illustrate the scope of each tool, possible research questions or challenges are listed in Table 2 together with the SIAC tools that implement functions for addressing each item.

Table 2. Contribution of SIAC tools to assessment challenges and research questions.

Challenge, research question	SIAC functional scope	SIAC tool module
Determine approximate, species-specific values for selected tree traits, e.g., crown diameter	Trait modelling	TCAC
Determine the total tree cover for an area of interest based on point features representing trees	Modelling of tree cover	
Identification of solitary trees and rows of trees	Classification of spatial-morphological patterns	
Obtain the total abundance of tree features, the relative abundance of tree species, and identify urban food forest entities	Assessment of tree species richness and diversity	
Identification of street trees and of trees adjacent to buildings	Assessment of spatial-topological relationships	TOPOMOD
Assessment of tree cover connectivity, including connected components, and fragmentation	Modelling of connectivity and fragmentation	
Identification of tree cover features that are important for maintaining connectivity	Modelling of connectivity and fragmentation	
Determination of tree cover and impervious cover for spatial units of analysis.	Assessment of plots	SITA
Determination of tree cover and impervious cover within a given radius from randomly selected locations	Assessment of randomly sampled locations	
Identify (tiny) forests based on formal rules	Assessment of total forest cover	COIN
Determine the amount of air pollutants removed by tree-based entities	Estimation of regulation of air quality	
Determine the amount of carbon stored by tree-based entities	Estimation of carbon sequestration and storage	

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The SIAC tools used to address research questions and challenges as outlined in Table 2 each require certain input data and parameters as input, and provide certain feature layers as output. Figure 6 and Figure 7 summarize required parameters and flow of data between the various SIAC tools. It becomes clear that in particular two layers are core feature layers: (i) the tree cover layer; and (ii) the layer with local traits as assessed by SITA. The former layer is used primarily for the modelling of spatial-topological relationships, of connectivity and fragmentation, and as input to SITA. It may be derived from a tree cadastre, i.e., at a minimum, point features of trees, that is provided to TCAC as input (cf. Figure 6). However, this layer may also be substituted with a pre-existing polygon feature layer that represents tree cover. Such a layer is, e.g., the Urban Atlas Street Tree Layer (Copernicus, 2018). The latter layer is the output of SITA, and is mostly used for the assessment of tree cover-related benefits (cf. Figure 7).

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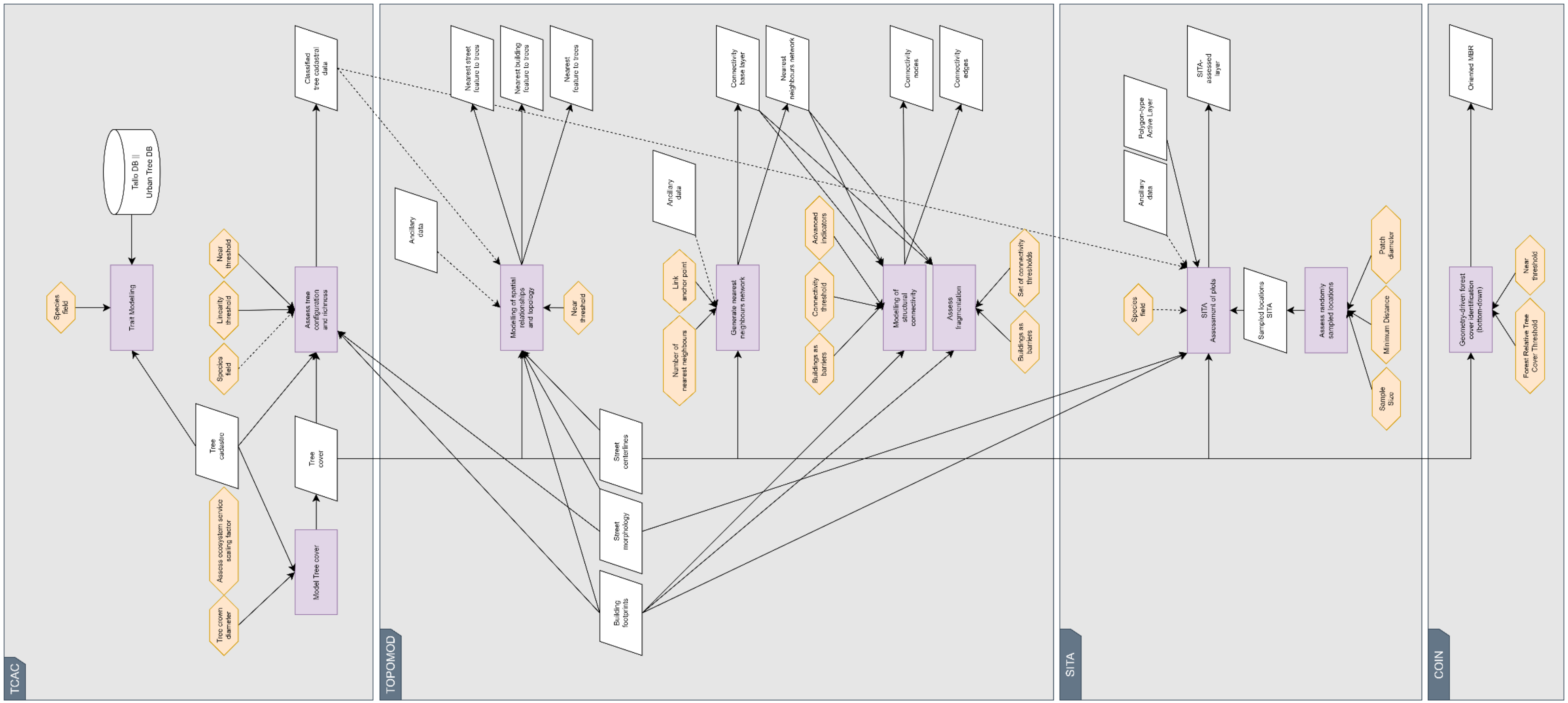

Figure 6. SIAC tools with input layers, parameters, and outputs, and interdependencies between data and tools (part 1). See Figure 7 for legend.

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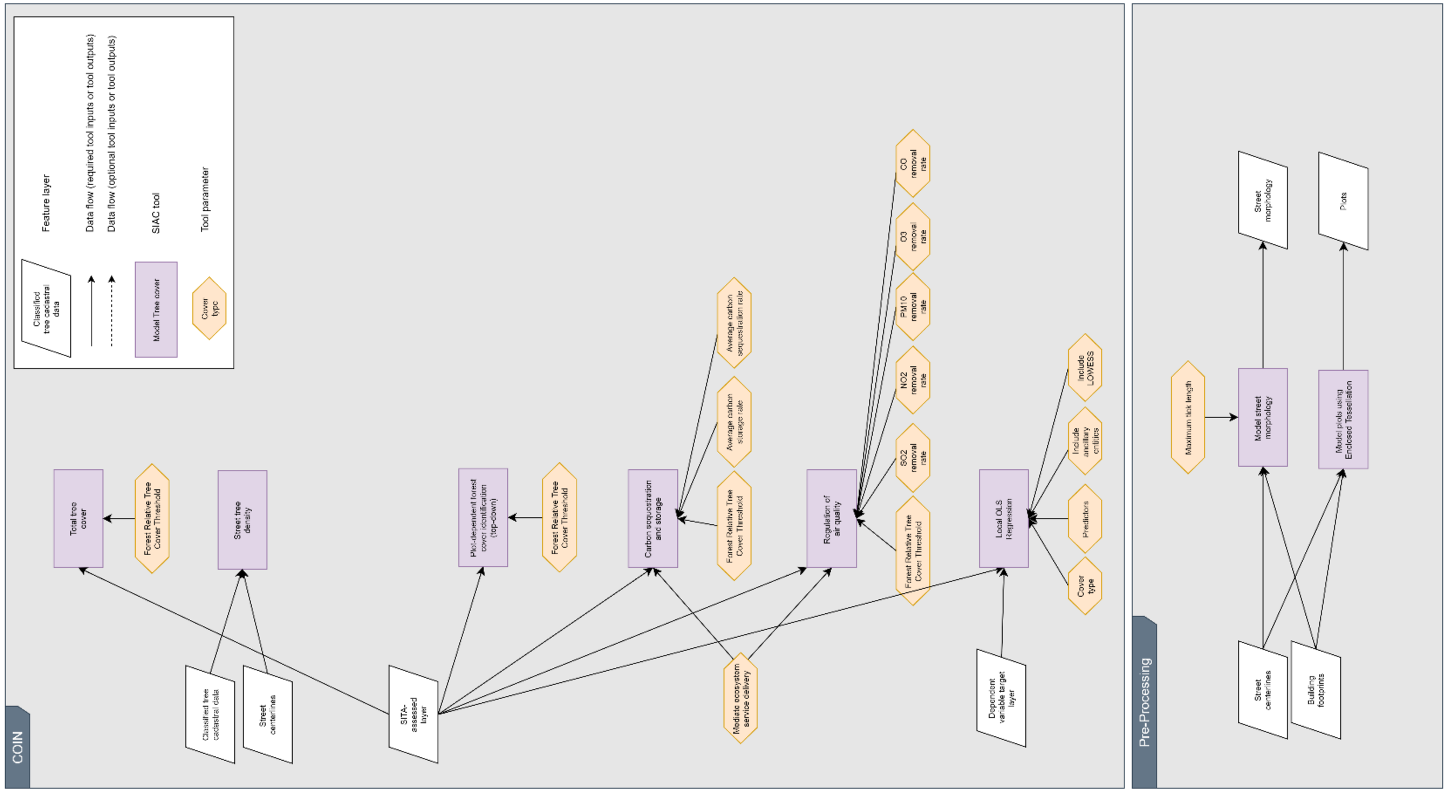

Figure 7. SIAC tools with input layers, parameters, and outputs, and interdependencies between data and tools (part 2).

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Tree Configuration Assessment and Classification (TCAC)

Modelling of tree traits from external databases

Derive tree traits, specifically tree crown diameter, from external databases based on tree species. Traits are derived by averaging respective database entries at the species level. The function utilizes one of the following supported external databases; either database may be imported into SIAC from the Model/Import menu:

- TALLO database (Jucker et al., 2022)
- Urban Tree Database (McPherson et al., 2016)

Tool inputs

Table 3. TCAC (Modelling of tree traits) input layers and parameters.

Data or Parameter	Data Type	Description
Tree cadastre	Point feature layer	Point location of trees
External database	CSV	Prior imported database, as selected by user when invoking the tool.
Tree genus/tree species	Field name or None	Name of field of the attribute table indicating tree genus or tree species. If a field is selected, then tree species richness and diversity parameters are assessed. This parameter is optional.

Tool outputs

The input layer is augmented by the following fields.

Table 4. TCAC (Modelling of tree traits) fields.

Field	Description
CROWN_DIA	Tree crown diameter (in m), as averaged from the external data at species level.

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Limitations

- Depending on the input layer entries for the species attribute and the species entries in the external database (data quality), automatic matching of entries may be unsuccessful.
- At this time, no sub-queries are supported that define subsets of database entries used for averaging tree data.

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Modelling of tree cover

Model tree cover based on point features representing individual tree entities. Tree cover is modelled by buffering of tree locations, with buffer distance either derived from an assumed tree crown diameter (user-defined fixed crown diameter value), or from a specified field from the layer's attribute table that holds a tree-specific crown diameter value (dynamic crown diameter value). Resulting tree canopy features are returned as tree cover layer (Figure 8).

Moreover, the modelling of tree cover supports a simplistic mechanism for modelling of tree health impacts on ecosystem services delivery. The potentially diminishing delivery of ecosystem services due to bad tree health, e.g., due to severe impacts of drought, may be expressed internally as so-called scaling factor, that is added to the tree cadastre layer's attribute table. This scaling factor is tree specific and should be chosen in the range [0;1]. Here, a scaling factor equal to 1 would indicate healthy trees that are, e.g., unaffected by drought, and that therefore deliver ecosystem services at their full potential. Conversely, a scaling factor of 0 would indicate trees that may be dead or fallen, i.e., that do not deliver ecosystem services any further. If the assessment of such an ecosystem service scaling factor is enabled by the user, the field from the attribute table holding the tree-specific scaling factors needs to be specified accordingly. TCAC will then average these tree-specific values at the tree canopy feature level.

Tool inputs

Table 5. TCAC (Modelling of tree cover) input layers and parameters.

Data or Parameter	Data Type	Description
Tree cadastre	Point feature layer	Point location of trees
Tree crown diameter	Float or layer attribute/field	Tree crown diameter (in m): Fixed value or name of field containing tree crown diameter values (in m) from the tree cadastre attribute table, as specified by the user.
Assessment of ecosystem service scaling factors		If enabled, a user-specified field from the layer is used to average a scaling factor for ecosystem service delivery.

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Tool outputs

Table 6. TCAC (Modelling of tree cover) output layers.

Data or Parameter	Data Type	Description
Tree Cover	Polygon feature layer	Modelled tree canopies, with overlapping canopies dissolved into single features. Each canopy polygon holds the corresponding, classified tree configuration. This layer is a crucial output layer used in other SIAC tools.

The TCAC (Modelling of tree cover) returns a tree cover layer. The following information is reported:

- Total tree abundance, i.e., total number of assessed trees;
- Total number of tree canopies, i.e., tree cover by solitary or grouped trees.

Table 7. TCAC (Modelling of tree cover) fields.

Field	Description
SIACID	Tool-internal feature identifier
ENTITY_AREA	Area (in m^2) of the corresponding entity, i.e., of the canopy cover.
ESS_K	Ecosystem service scaling factor, averaged at tree cover/tree cover level. Optionally included if respective assessment has been enabled by the user.

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Figure 8. Exemplary depiction of tree cover layer features. Features in the tree cover layer are determined based on modelled tree crown features, with overlapping tree crowns being considered part of a given tree canopy. The respective oriented minimum bounding rectangles, that, e.g., support the assessment of linearity of tree plantings, are shown as red rectangles
(Photo credits: Gokhun Guneyhan, Unsplash License).

Limitations

- The assessment of tree cover is based on tree crown diameter. The uncertainties regarding the chosen tree crown diameter value govern uncertainties regarding tree cover estimation.
- The scaling factor to represent potentially diminishing ecosystem services delivery by tree entities as a function of tree health is simplistic.

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Assessing tree configuration and richness

Assess the spatial tree configuration, i.e., determine a spatial-morphological classification of tree-based entities. This classification includes an identification of solitary trees, or grouped (clustered) trees. For grouped trees, it is attempted to assess linearity of planting patterns. This assessment of linearity is based on an adaptation of the Ellipse Axis Ratio metric outlined by Stojmenović et al. (2008) and is based on the elongation of an oriented minimum bounding rectangle (Figure 8). For grouped trees, it is furthermore attempted to assess the regularity or dispersion of tree features, based on Nearest Neighbour Network statistics. Similar to clustered tree features, also for solitary trees, linearity of planting arrangements, e.g., as wider-spaced rows of trees, is tested, based on spatial relationships to near tree features.

If the user specifies a field contained in the tree cadastral data indicating tree genus or tree species, then TCAC additionally derives basic richness and diversity indices. See below for a more detailed description of computed measures.

Tool inputs

Table 8. TCAC (Assess tree configuration and richness) input layers and parameters.

Data or Parameter	Data Type	Description
Tree cadastre	Point feature layer	Point location of trees
Tree Cover	Polygon feature layer	This dataset is generated by TCAC. Alternatively, another polygon feature layer may be provided.
Tree genus/tree species	Field name or None	Name of field of the attribute table indicating tree genus or tree species. If a field is selected, then tree species richness and diversity parameters are assessed. This parameter is optional.
Linearity threshold	Double in the range 0 to 1 inclusive.	Threshold indicating linearity of features, where linearity is assumed if (1–feature elongation) > linearity threshold. The default value is 0.5.
Near threshold	Double	Threshold indicating a distance (in m) that defines near proximity. In the assessment, features of a distance within this threshold are considered near, and are thus included in the assessment of spatial patterns.

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Tool outputs

Table 9. TCAC (Assess tree configuration and richness) outputs.

Data or Parameter	Data Type	Description
Classified tree cadastral data	Point feature layer	Tree cadastral data layer with augmented information (TREE_CLASS). This layer is a crucial output layer used in other SIAC tools.

TCAC (Assess tree patterns and configuration) returns a classified tree cadastre layer and augments the tree cover input layer with additional fields that indicate, e.g., tree abundance at local level (per tree cover), linearity, and the classification of tree-based entities etc. When a tree genus/tree species field has been specified, this function also assesses tree species richness and diversity. Richness is the overall observed genus or species count (i.e., determined on the basis of unique values of the specified field) at local level (per tree cover) and at global level (dataset level). In addition, the following richness and diversity indicators are reported:

- Total richness (i.e., number of unique species/genus in the dataset);
- Menhinick's index;
- Margalef's index;
- Simpson’s Index;
- Shannon-Wiener Diversity Index;
- Pielou Index of Evenness; and
- the five most-commonly observed species/genus based on their relative abundance;
- a rank-relative abundance plot is produced.

In addition, against a list of user-specified genus or species of fruit trees, presence or absence of fruit trees as a reflection on urban food forest entities is conducted. The fields described in Table 13 are added to the classified tree cadastral data layer and/or the tree cover layer. The summarized tree richness and diversity data is stored internally, and may be exported to an Excel spreadsheet from the Model/Export menu.

- Although this function specifically references fruit trees due to the perceived importance of the urban food forest, the provided mechanism may nonetheless be adapted to other kinds of tree genus or tree species of interest, by providing the respective items in the input list.
- The corresponding function in the Model/Export menu is disabled if no tree richness and diversity data is internally stored.

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Table 10. TCAC (Assess tree configuration and richness) fields.

Field	Description
SIACID	Tool-internal feature identifier.
SIACTRID	Tool-internal feature identifier.
TREE_IDS	Identifiers of the trees contained in the modelled canopy cover (Note: also for the minimum bounding rectangle, this refers to the tree identifiers of the trees that are contained in the modelled canopy cover). The identifiers refer to ids in the tree cadastral data.
OMBR_ANGLE	Orientation (degrees) of the oriented minimum bounding rectangle.
OMBR_WIDTH	Width (m) of the oriented minimum bounding rectangle.
OMBR_HEIGHT	Height (m) of the oriented minimum bounding rectangle.
LINEARITY	The linearity of the oriented minimum bounding rectangle, defined as (1 –Elongation)
TREE_COUNT	Number of trees contained in the modelled canopy/tree cover (Note: also for the minimum bounding rectangle, this number refers to the trees of the corresponding modelled canopy cover. It may differ from the number of trees contained in the oriented minimum bounding rectangle, if there are other canopies overlapping the minimum bounding rectangle).
OBSERVED_DIST	Observed averaged distance between trees contained in the modelled canopy cover, from a Nearest Neighbour Index analysis (Note: For solitary trees, a default value of 0 is stored to the attribute table)
EXPECTED_DIST	Expected averaged distance between trees contained in the modelled canopy cover, from a Nearest Neighbour Index analysis, for a hypothetical random distribution (Note: For solitary trees, a default value of 0 is stored to the attribute table).
NN_INDEX	Nearest Neighbourhood Index. Values lower than 1 indicate clustering, values higher than one indicate dispersion or regular arrangement (Note: For solitary trees, a default value of 1 is stored to the attribute table).
NN_ZSCORE	Z-Score of Nearest Neighbourhood Index analysis (Note: For solitary trees, a default value of 0 is stored to the attribute table).
TREE_DENSITY	The tree density for the modelled canopy cover, i.e., number of trees per unit area (trees per ha).
TREE_CLASS	Tree configuration classification (see Table 11).
S_TREE_CLASS	Solitary trees are considered not spatially clustered/grouped, i.e., tree cover of solitary trees contains are formed by one given tree entity. However, also solitary trees may form patterns resembling, e.g., loose rows or clusters. Such spatial configurations are expressed through the Solitary tree configuration classification (see Table 12).

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Table 11. Description of classes indicating tree morphology/spatial configurations of tree patterns.

Class	Description
solitary	Solitary (single) trees
clustered-grouping	Trees in a clustered, two-dimensional arrangement
dispersed-or-regular-grouping	Trees in a dispersed, or otherwise regularly arranged two-dimensionally grouped pattern
clustered-linear-grouping	Trees arranged (quasi- or near-)linearly, with tree distances speaking to a likely clustering of trees within the tree line
dispersed-or-regular-linear-grouping	Trees arranged (quasi- or near-)linearly, with tree distances speaking to a dispersed, or otherwise regular arrangement of trees within the tree line

Table 12. Description of classes indicating spatial configurations of solitary trees.

Class	Description
solitary-single-tree	A solitary tree with no other near tree features.
solitary-tree-paired	A solitary tree with a single other near tree feature.
solitary-potential-row	A solitary tree with (more than one) near tree features, that appear to form a linear pattern.
solitary-other-grouping	A solitary tree with (more than one) near tree features, that do not appear to form a linear pattern.

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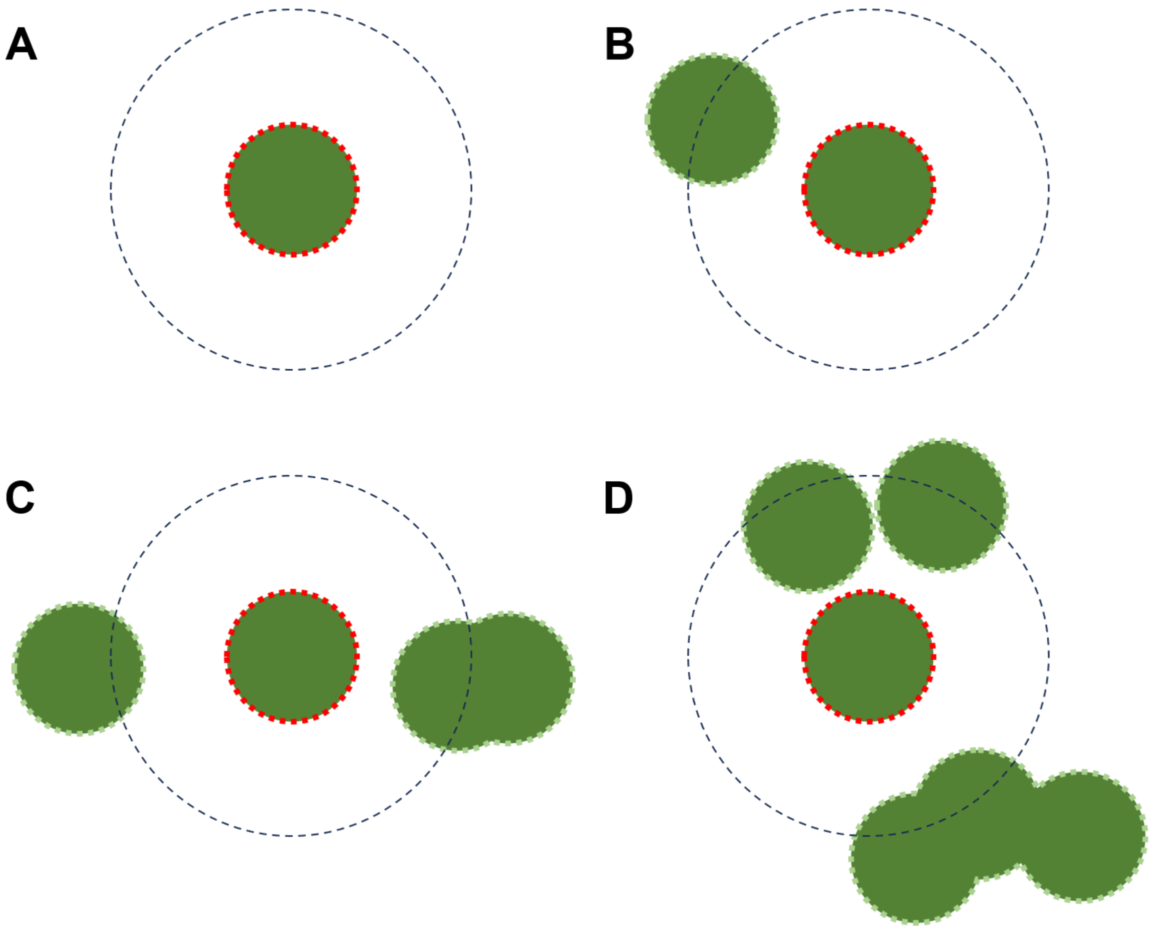

Figure 9. Examples for spatial configurations of solitary trees. In these examples, the solitary tree at the centre, marked with red outline, would receive the classes as indicated. For reference, the applicable near threshold that governs the assessment is indicated as dashed black circle. (A) solitary-single-tree; (B) solitary-tree-paired; (C) solitary-potential-row; and (D) solitary-other-grouping.

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Table 13. TCAC field descriptions (richness and diversity assessment).

Field	Description
TREE_RICHN	The tree genus/tree species richness of the corresponding spatial unit.
TREE_SPECIES	Genus or species identified within the corresponding spatial unit. Unique values for observed genus/species are provided, separated by comma.
TREE_SPECIES_CNT	Genus or species identified within the corresponding spatial unit, and species abundance, i.e., number of trees per species. This field serializes richness and diversity assessment at the level of the corresponding spatial unit in the form species-name=species-count|species-name=species-count|…
HAS_FRUIT_TR	Boolean field indicating the presence (value equal to 1) or absence (value equal to 0) of fruit trees within the corresponding spatial unit. Presence of fruit trees is determined on the basis of a genus/species list, that is matched against the user-defined tree genus/tree species attribute field.
FRUIT_TR_COUNT	Total number of fruit trees within the corresponding spatial unit.
FRUIT_TR_SHARE	Share of fruit trees amongst all trees within the corresponding spatial unit.

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Computation of richness and diversity indicators

Menhinick's index:

$$D_{Mh} = \frac{S}{\sqrt{N}} \tag{1}$$

Margalef's index:

$$D_{Mg} = \frac{S-1}{\ln N} \tag{2}$$

Simpson's index:

$$D = \sum_{i=1}^{S} \left(\frac{n_i}{N}\right)^2 \tag{3}$$

Shannon-Wiener Diversity Index:

$$H' = -\sum_{i=1}^{S} \left(\frac{n_i}{N}\right) \ln\left(\frac{n_i}{N}\right) \tag{4}$$

Brillouin Index:

$$H = \frac{1}{N}\left(\ln N! - \sum_{i=1}^{S} \ln(n_i!)\right) \tag{5}$$

Pielou Evenness Index:

$$J' = \frac{H\prime}{\ln S} \tag{5}$$

with symbols denoting the following:

S … tree species richness
n_i … total number of individuals of the ith species
N … total tree abundance (total number of trees)

Indices based on Fedor and Zvaríková (2019), Roberts (2019).

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Limitations

- The classification of spatial patterns of tree features is a prototype implementation. Tree planting patterns are considered as follows: (i) at the solitary tree level; and (ii) at the tree cover/canopy) level. Linearity is assessed at these levels as follows: (i) for solitary trees under consideration of near tree features; and (ii) for the canopy, as a function of the tree cover extent for the whole tree group. Therefore, TCAC is thus currently unable to assess sub-patterns within an overall tree pattern, for example, tree lines within a larger two-dimensional, dispersed group of trees.
- The identification of tree lines is associated with considerable uncertainty as it may not consider the following cases correctly: double tree lines planted next to each other (more likely assessed as two-dimensional grouping); trees lines with changes in orientation or direction, for example, at intersections, or along curved roads.

The core output layer of TCAC is the tree cover layer. When such a tree cover layer is available, it may also be used directly as input to subsequent SIAC tools, and TCAC tool may be skipped. However, this may reduce level of detail of subsequent analysis, as certain fields may not be included in the tool outputs.

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Topology and Spatial Relationship Modelling (TOPOMOD)

Modelling of spatial relationships and topology

Assess spatial relationships between (groups of) trees and other features, including roads, buildings. More specifically, the TOPOMOD model of spatial relationships and topology assesses associations of trees with street and building features. In so-doing, the tool intents to identify street trees or building-related greenery. The tool seeks to determine the following spatial-topological traits:

- *Association with street features/ancillary entity classes*: This trait is derived from the spatial relation between tree features and/or tree cover features and street morphology or other polygon-type features from ancillary classes defined by the user as target features. Association (containment) is determined separately for tree cover features and tree features:

  For tree cover features intersecting target features, they are considered to be associated with streets: Association may therefore refer to full containment or partial containment and thus at least partial adjacency. Therefore, with partial containment considered as valid association, it also needs to be noted that tree cover features may be associated with multiple target feature types, e.g., be associated with streets and simultaneously with urban green spaces.

  For tree features, a spatial intersect determines if they are associated with the target feature class.

- *Adjacency or near proximity to buildings as potential building-related tree entities*: This trait is derived based on shortest line features from tree features to building features. TOPOMOD assumes a direct adjacency if the shortest line from a given tree feature to its nearest building feature is not intersected by a street feature. Adjacency relationship is rejected when a shortest line intersects a building footprint.

- *Adjacency or near proximity to streets as potential street tree entities*: This trait is derived based on shortest line features from tree features to street features. TOPOMOD assumes a direct adjacency if the shortest line from a given tree feature to its nearest street feature is not intersected by a building feature. Adjacency relationship is rejected when a shortest line intersects a street centerline.

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Tool inputs

Table 14. TOPOMOD (Modelling of spatial relationships and topology) input layers and tool parameters.

Data or Parameter	Data Type	Description
Tree Cover	Polygon feature layer	This dataset is generated by TCAC. Alternatively, another polygon feature layer may be provided.
Streets	Line feature layer	Street centerlines.
Street morphology	Polygon feature layer	Street morphology. This dataset can be generated with the DATA PROCESSOR tool, if not available.
Building footprints	Polygon feature layer	Building geometries/footprints.
Classified tree cadastral data	Point feature layer	Optional. This dataset is generated by TCAC.
Ancillary Data	Polygon feature layer	Optional, ancillary data layers may be defined as needed. This function considers the following entities: Urban green space, water bodies.

The following spatial relationships are assessed for user-defined entity types:

- For urban green spaces, association/containment and adjacency are determined.
- For water bodies, only adjacency is determined.

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Tool outputs

The tool outputs several layers of shortest line features between tree or tree cover features to other entities, e.g., to buildings, to streets, or to ancillary classes/entity types etc.

Table 15. TOPOMOD (Modelling of spatial relationships and topology) outputs.

Data or Parameter	Data Type	Description
Nearest street feature to trees	Line feature layer	Shortest line features indicating nearest target feature of interest to tree or tree cover features, with Euclidian distances (in m).
Nearest building feature to trees	Line feature layer	Shortest line features indicating nearest target feature of interest to tree or tree cover features, with Euclidian distances (in m).
Nearest feature to trees	Line feature layer	Shortest line features indicating nearest target feature of interest (ancillary class) to tree or tree cover features, with Euclidian distances (in m).

Based on the identified links, TOPOMOD augments the TCAC-derived layers "Classified tree cadastral data" and "Closed Tree Canopy Cover" with additional fields, indicating the following information: Fields with prefix IN indicate association/containment, as determined using spatial intersects. Fields with prefix DIST store Euclidian to nearest feature of interest, and fields prefixed with ADJ indicate adjacency or near proximity.

In addition, TOPOMOD Modelling of spatial relationships and topology seeks to identify the number of trees contained within street segments, as well as the number of trees considered near a given street segment, as well as near buildings. Results of this assessment are stored to the respective layers, i.e., street morphology as well as buildings, as fields TR_CNT_IN and TR_CNT_NEAR, respectively.

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Table 16. TOPOMOD (Modelling of spatial relationships and topology) fields.

Field	Description
IN_{*name*}	Boolean indication of association/containment of a tree or tree canopy feature within feature class of interest, e.g., street, or ancillary classes/entity types such as urban green spaces. Presence of an association is indicated by a value of 1, indicating (at least partial) containment.
DIST_{*name*}	Euclidian distance (in m) to nearest within feature class of interest, e.g., street, or ancillary classes/entity types such as urban green spaces (to edge/perimeter).
NEAR_{*name*}	Boolean indication of adjacency or near proximity of a tree or tree canopy feature to another feature class of interest, e.g., street, or ancillary classes/entity types such as urban green spaces. Likely adjacency is indicated by a value of 1.
TR_CNT_IN	Count, i.e., number of trees within (intersecting) a given feature.
TR_CNT_NEAR	Count, i.e., number of trees considered near to a given feature. A tree is considered near if a shortest line between a given feature and a tree in question is neither crossing a feature considered a barrier, nor is the distance between both features exceeding the near threshold defined by the user.

Limitations

- Assessed spatial-topological traits are basic and represent a prototypical implementation.
- The assessment of adjacency or near proximity is based on shortest lines between relevant features, and potential intersections of these shortest lines with features that may inhibit an assumption of adjacency or near proximity (features acting as barriers). Such modelling of barriers is a basic, simplistic approach. Moreover, at this moment, only a single shortest line is evaluated. Therefore, it may not consider adjacencies or near proximities to near but more-distant features.
- The user-defined near threshold may significantly impact outputs of this tool. Choice of this value is associated with uncertainty.

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Modelling of connectivity and fragmentation

Generate nearest neighbours network

Constructs a network of *n* nearest neighbours by generating shortest lines (links) from each tree cover feature to the specified number of tree cover features (neighbours) as nodes. The resulting nearest neighbours network provides the basis for the modelling of structural connectivity and of fragmentation.

Depending on the feature count and desired number of neighbours, this task may be computationally heavy. It is suggested to gradually increase the number of nearest neighbours used, as deemed necessary.

Tool inputs

Table 17. TOPOMOD (Generate nearest neighbours network) input layers and parameters.

Data or Parameter	Data Type	Description
Tree cover	Polygon feature layer	A layer describing tree cover. This dataset is generated by TCAC or an alternative polygon feature layer may be provided.
Number of nearest neighbours	Integer	Number of neighbours used to construct connectivity network. Smaller number is faster but may not depict all relevant links.
Link anchor point		User-selected anchor point for edge construction; either from edge to edge, or from centroid to centroid.
Ancillary Data	Polygon feature layer	Optional. Ancillary data layers may be defined as needed. This function considers the following entities: Urban green space, forest, that are included in the assessment as nodes, if present.

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Tool outputs

Table 18. TOPOMOD (Generate nearest neighbours network) outputs.

Data or Parameter	Data Type	Description
Connectivity base layer	Polygon feature layer	The base layer including nodes for assessment of connectivity, that furthermore integrates all tool-derived and user-specified data for connectivity analysis.
Nearest neighbours network	Line feature layer	Shortest line features (links) from each base layer feature (node) to its *n* nearest neighbours in the base layer. Distance equals Euclidian distance.

The function returns a connectivity base layer, that includes all identified nodes as polygon features, as well as the nearest neighbours network layer, that contains shortest lines features depicting links between tree canopies.

Limitations

- The tool requires the number of neighbours to be specified by the user. This may lead to an underestimation of connectivity through omission of relevant edges, if the number of neighbours (an thus, the theoretical maximum number of links at the feature level) is set too small. This may be mitigated by reviewing the maximum observed number of links metric, and adjusting the number of nearest neighbours to be used accordingly.

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Modelling of structural connectivity

The TOPOMOD “Modelling of structural connectivity” function aims at identifying structural connectivity and connectivity relationships between tree canopies. Using the nearest-neighbour network that is generated by the TOPOMOD “Generate nearest neighbours network” tool, a graph-based approach to assessing connectivity indicators is adapted.

Connectivity modelling is implemented based on the networkx package (Hagberg et al., 2008). Tree cover features from the connectivity base layer are introduced into an undirected graph as nodes, with node capacities equal to the respective tree cover feature area. If present in the connectivity base layer, urban green space and/or forest entities as ancillary classes are represented as nodes as well. (Undirected) edges in the graph are derived based on the nearest neighbours network layer. It is assumed that nodes are connected if (i) the distance between two given nodes, that is represented through a shortest line (link) in the nearest neighbours network layer, is lower than or equal to the user-specific connectivity threshold; and (ii) the potential edge between two given nodes does not intersect a feature that functions as barrier, thus inhibiting connectivity. Following Chan et al. (2021), here, particularly anthropogenic structures, i.e., buildings, are considered barriers to connectivity (it may however be opted to ignore buildings as barriers entirely).

Based on these assumptions, valid links between two nodes are introduced into the graph as edges. Selected metrics are determined on the complete graph, or subgraphs representing connected components. These metrics include:

- Component count, and number of patches (nodes) per component;
- Patch capacities (per node and per component);
- Characteristic path lengths and number of links per patch (per node);
- Patch eccentricity, closeness centrality, degree of centrality, and betweenness centrality (per node);
- Graph diameter (per component);
- Mean size of the components, size of the largest component;
- Identification of bridges (for edges), nodes associated with bridges (for nodes that form undirected endpoints of bridges);
- Identification of articulation points (patch respectively node level).

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Tool inputs

Table 19. TOPOMOD (Modelling of structural connectivity) input layers and parameters.

Data or Parameter	Data Type	Description
Connectivity base layer	Polygon feature layer	The base layer for assessment of connectivity that integrated all tool-derived and user-specified data for connectivity analysis.
Nearest neighbours network	Line feature layer	Shortest line features (links) from each base layer feature (node) to its *n* nearest neighbours in the base layer. Distance equals Euclidian distance.
Connectivity Threshold	Double	Assumed maximum connectivity threshold, e.g., in terms of maximum dispersal distance. Links with a length longer this threshold are not included in the undirected graph as edges, and thus, are excluded in the computation of indices. The default value is 100m, following Chan et al. (2021).
Building footprints	Polygon feature layer	Building geometries/footprints.
Buildings as barriers		Indicates whether buildings act as barriers on edges, thus affecting connectivity.
Advanced indicators		Each checked indicator is determined.

Advanced indicators include PATCH_CCE, PATCH_EC, PATCH_DEG, PATCH_BETWE, and COMPONENT_GD, that can individually be selected for computation as required. Calculating advanced indicators may increase computation time considerably. Whilst computing the basic indicator set for a graph containing ~26000 nodes from a nearest neighbour network of 10 nearest neighbours takes between 1 to 2 minutes, computation of all advanced indicators may take upward of 1 hour for the same graph.

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Tool outputs

Table 20. TOPOMOD (Modelling of structural connectivity) outputs.

Data or Parameter	Data Type	Description
Connectivity Nodes	Point feature layer	Layer representing nodes in terms of centroids derived from closed tree canopy cover layer for the purpose of easier visualization of structure.
Connectivity Edges	Line feature layer	This layer is based on the nearest neighbours network layer, that is augmented with fields indicating results of assessing each edge properties with respect to specific connectivity threshold or edge-to-urban morphology relationships.

The attribute table of the Connectivity Edges layer is augmented with fields that indicate certain assessment results. In addition, the Closed Canopy Cover layer is augmented with additional data. Refer to the following tables for a description of fields.

Table 21. TOPOMOD (Modelling of structural connectivity) Connectivity Edges layer fields.

Field	Description
LINK_OBSTR	Boolean value indicating whether a link is unobstructed (valid link, as it does not intersect a building; indicated by a value equal to 0), or obstructed (link not counted; indicated by a value equal to 1).
LINK_RANGE	Boolean value indicating whether a given link's length exceeds the user specified connectivity threshold (invalid link; value equal to 1) or is within the connectivity threshold (valid link; value equal to 0).
distance	Planar length (in m) of the shortest line feature, i.e., edge-to-edge or centroid-to-centroid distance between the two tree canopies in question.
LINK_VALID	Boolean value indicating of a certain link is considered in the computation of indices (value equal to 1) or dropped (value equal to 0). A link is dropped if LINK_OBSTR or LINK_RANGE is equal to 1.
IS_BRIDGE	Boolean value indicating if a given edge forms a bridge. A bridge is an edge whose removal would increase the overall number of components. A value of 1 indicates that the edge has been identified as a bridge.

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Table 22. TOPOMOD ((Modelling of structural connectivity) Connectivity Nodes fields.

Field	Description
PATCH_LNK	The number of links to other nodes (tree canopy features), here, based on shortest lines that are considered valid links.
PATCH_CPL	Characteristic path length of tree canopy links, i.e., average Euclidian distance (in m) to linked tree canopy features (edge-to-edge).
PATCH_A	Capacity of the patch, i.e., at this time, by default, the area (in m^2) of the corresponding tree canopy.
PATCH_CCE	Patch closeness centrality, i.e., reciprocal of the average shortest path distance to a patch over all n-1 reachable nodes. Edge distance is used as attribute in shortest path calculation.
PATCH_EC	Patch eccentricity, i.e., maximum distance from a given patch to all other patches of the component's subgraph. Eccentricity is determines using edge distance as weight.
PATCH_DEG	Degree of centrality, i.e., the fraction of nodes a given node is connected to in the component's subgraph. Belongs to the advanced connectivity indicators due to potentially high computational demand.
PATCH_BETWE	Betweenness centrality, i.e., the fraction of shortest paths traversing through a given node. Edge distance is used as weight in the computation.
IS_BRIDGE	Boolean value indicating if a given node is participating in forming a bridge. A bridge is an edge whose removal would increase the overall number of components. A value of 1 indicates that a patch has been identified as (undirected) endpoint of a bridge.
IS_ARTICULATE	Boolean value indicating if a given node is an articulation point. The removal of an articulation point and of its associated edges would increase the overall number of components. A value of 1 indicates that a patch has been identified as articulation point.
COMPONENT_ID	The identifier of the component the canopy is associated with. This field is used to distinguish the connected components from each other.
COMPONENT_NK	Number of patches (nodes) in a given component.
COMPONENT_A	Total capacity of the component, i.e., sum of patch capacities of contained patches.
COMPONENT_GD	Graph diameter of the component, i.e., *max*(PATCH_EC) of the patches of the component.

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In addition, the following items/indicators are reported:

- Included barriers;
- Connectivity threshold;
- Number of patches considered;
- Patch capacities (with respect to individual tree canopies)*: Minimum, mean, and maximum patch capacity (at this time, area in m²)*
- Mean characteristic path length*: The mean and standard deviation of characteristic path length (in m), i.e., average length of edges, and standard deviation of average length, at dataset level.*
- Number of links*: The minimum, average and maximum number of links observed at dataset level.*
- Number of components*: The number of components.*
- Size of the components, i.e., capacity (being area in m² at this time): Size of the smallest (minimum capacity) component, mean size of the components, and size of the largest component (maximum capacity).

Limitations

- The tool requires a distance-based connectivity threshold to be specified by the user. This threshold represents, e.g., equivalent to a species-specific dispersal distance.
- The tool does not consider travel cost. Edge weights are only Euclidian distance-based, and only a topological view is established. I.e., no corridors etc. are depicted.
- The identification of bridges and articulation points is based only on a topological-structural view, i.e., their identification is based on an increase in fragmentation by their removal due to a resulting higher number of components. However, removal of bridges or articulation points must not necessitate loss of connectivity at the species-level.

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Assess fragmentation

Assess the level of fragmentation, i.e., the number of isolated components, across a range of connectivity thresholds.

Tool inputs

Table 23. TOPOMOD (Assess fragmentation) input data sources and tool parameters.

Data or Parameter	Data Type	Description
Connectivity base layer	Polygon feature layer	The base layer for assessment of connectivity that integrated all tool-derived and user-specified data for connectivity analysis.
Building footprints	Polygon feature layer	Building geometries/footprints.
Nearest neighbours network	Line feature layer	Shortest line features (links) from each base layer feature (node) to its *n* nearest neighbours in the base layer. Distance equals Euclidian distance.
Set of Connectivity Thresholds	Double values separated by semicolon	Assumed maximum connectivity threshold, e.g., in terms of maximum dispersal distance. Links with a length longer this threshold are not included in the computation of indices.
Buildings as barriers		Indicates whether buildings act as barriers on edges, thus affecting connectivity.

Tool outputs

For each threshold contained in the connectivity thresholds set, the following items/indicators are reported; additionally, a graph is returned that plots the number of components and the mean size of components over thresholds/distances:

- Number of components;
- Size of the components: Size of the smallest component, mean size of the components, size of the largest component.

Limitations

Please refer to TOPOMOD Modelling of structural connectivity limitations.

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Site assessment (SITA)

Assess plots

Whilst TCAC approaches a classification of tree morphology/grouping of individual trees, thus deriving indicators at the level of trees and resulting tree cover (closed canopy features), SITA addresses the assessment of spatial analysis units as areas of interest and derives—similar to TCAC—traits and/or indicators at the level of these spatial analysis units (hereafter also referred to as patches or plots, e.g., as derived by closed tessellation). SITA determines a range of traits at plot-level, e.g., the total and relative tree cover, building cover, or impervious area cover.

In the assessment of total and relative cover of selected entities, SITA attempts to topologically correct provided data, e.g., regarding overlaps of geometric feature representations (such as buildings within urban green spaces) that may typically be present in GIS data. Generally, geometric representations of building footprints are considered as correct reference, i.e., building footprints are subtracted from other layers such as streets in the estimation of total area covered by the other entity in question.

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Tool inputs

Table 24. SITA (Plot assessment) input layers and parameters.

Data or Parameter	Data Type	Description
User-defined active layer	Polygon feature layer	Layer defined as active layer, and that contains distinct patch geometries. SITA will assess properties (traits) for each distinct patch (polygon, plot) in this layer.
Tree cover	Polygon feature layer	A layer describing tree cover. This dataset is generated by TCAC or an alternative polygon feature layer may be provided.
Building footprints	Polygon feature layer	Building geometries/footprints.
Street morphology	Polygon feature layer	Street morphology. This dataset can be generated with the DATA PROCESSOR tool, if not available.
Classified tree cadastral data	Point feature layer	Optional. This dataset is generated by TCAC.
Tree genus/tree species	Text-type field of Tree cadastral data layer, or None	Optional. Field of the attribute table indicating tree genus or tree species. If a field is selected, then richness and diversity of trees is assessed. This parameter is optional and set in the TCAC options.
Ancillary Data	Polygon feature layer or Point feature layer	Optional. Ancillary data layers may be defined as needed to represent the following supported entities: Urban green space, water bodies, forest, amenity features. SITA supports polygon-type and point-type ancillary data layers. For polygon-type layers, total and relative cover are determined. For point-type layers, containment is determined.

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Tool outputs

The active layer is augmented with the fields listed in the following table.

Table 25. SITA (Plot assessment) fields.

Field	Description
TREE_COVER_AREA	Tree cover (in m²) for a given plot (polygon feature).
TREE_COVER_SHARE	Relative tree cover, i.e., share of tree cover for a given plot (polygon feature).
TREE_DENS	Optional output, written if classified tree cadastral data has been included in the model: Tree density in number of trees per hectare.
BUILDING_AREA	Built-up cover (in m²) for a given plot (polygon feature).
BUILDING_SHARE	Relative built-up cover, i.e., share of buildings/built-up for a given plot (polygon feature).
STREET_AREA	Area covered by streets (in m²) for a given plot (polygon feature).
STREET_SHARE	Relative street cover, i.e., share of area covered by streets for a given plot (polygon feature).
IMPERV_AREA	Impervious area (in m²) for the given plot (polygon feature). Here, impervious area is determined as the sum of total building cover and total street cover.
IMPERV_SHARE	Share of impervious area for a given plot (polygon feature).

For each polygon-type entity defined as ancillary data, total cover and relative cover are determined at plot level. For each point-type entity as ancillary data, containment is determined. If a tree genus/tree species field has been selected, similar to TCAC, SITA assesses selected indicators of richness and diversity. Please refer to Table 13 for a description of fields.

Limitations

- There may be inaccuracies in the determination of total and relative cover per entity type, particularly if topologically incorrect datasets are used as input layers (i.e., layers with overlapping geometries, or features of different entities overlapping across different layers).
- Supported entity types are limited.

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Assess randomly sampled locations

Similar to the assessment of plots/patches by SITA, this function determines total and relative tree cover for defined spatial analysis units. However, whilst the assessment of plots determines traits for distinct polygon features (e.g., plots) in a systematic manner, this function constructs a set of circular patches with user-specified radius/diameter as spatial analysis units at randomly sampled point locations. Therefore, first, *n* points are randomly sampled across the dataset; anchor points for the sampling of points are tree cover features, i.e., each sample point will be randomly located within a randomly sampled tree cover feature. Second, a circular patch is constructed around the sampled point locations, with the diameter/radius as specified by the user. Subsequently, third, traits are determined for these sample sites analogous to the SITA “Plot assessment” function. In so-doing, an approach by Ziter et al. (2019) is adapted for SIAC.

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Tool inputs

Table 26. SITA (Assessment of randomly sampled locations) input layers and parameters.

Data or Parameter	Data Type	Description
Tree cover	Polygon feature layer	A layer describing tree cover. This dataset is generated by TCAC or an alternative polygon feature layer may be provided.
Building footprints	Polygon feature layer	Building geometries/footprints.
Street morphology	Polygon feature layer	Street morphology. This dataset can be generated with the DATA PROCESSOR tool, if not available.
Sample size	Integer	Number of locations (points) to sample.
Minimum Distance	Float	Minimum distance (in m) between points to sample.
Patch Diameter	Float	Diameter (in m) of the circular patch to be constructed at each randomly sampled point location.
Classified tree cadastral data	Point feature layer	Optional. This dataset is generated by TCAC.
Tree genus/tree species	Text-type field of Tree cadastral data layer, or None	Optional. Field of the attribute table indicating tree genus or tree species. If a field is selected, then richness and diversity of trees is assessed. This parameter is optional and set in the TCAC options.
Ancillary Data	Polygon feature layer or Point feature layer	Optional. Ancillary data layers may be defined as needed to represent the following supported entities: Urban green space, water bodies, forest, amenity features. SITA supports polygon-type and point-type ancillary data layers. For polygon-type layers, total and relative cover are determined. For point-type layers, containment is determined.

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Tool outputs

Table 27. SITA (Assessment of randomly sampled locations) outputs.

Data or Parameter	Data Type	Description
Sampled Locations SITA	Polygon feature layer	Layer holding all constructed circular patch features.

For each polygon-type entity defined as ancillary data, total cover and relative cover are determined at plot level. For each point-type entity as ancillary data, containment is determined. The fields written by this function are analogous to those written by SITA ”Plot assessment” tool. Please refer to Table 25.If a tree genus/tree species field has been selected, similar to TCAC, SITA assesses selected indicators of richness and diversity. Please refer to Table 13 for a description of fields.

Limitations

Please refer to SITA Assess plots tool for limitations.

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Computation of Indicators (COIN)

COIN seeks to provide a rapid, indicator-based assessment of tree-based entities (UF-NBS) conditions and broad, first estimates of potential benefits provided by such UF-NBS entities. Indicators include, e.g., total tree cover or forest cover, based on properties (traits) assessed at the feature level, and implementing formal definitions of entities as outlined in Scheuer et al., (2022). The assessment of benefits by COIN is conceptually linked to ecosystem services, i.e., COIN seeks to estimate the delivery of selected ecosystem services, mainly as a function of tree cover.

Total tree cover

Determines total tree cover area (in ha) based on the active layer, and adds tree cover area to the input layer as field. Essentially, if no ancillary classes are included in the model, based on SITA-assessed traits, tree cover is equal to the (modelled or user-provided) tree cover.

However, if forest has been included in the model as ancillary class, then total tree cover at the feature level is estimated as the sum of (modelled or user-provided) tree cover, and assumed effective forest-based tree cover. The effective forest-based tree cover is derived from applying the relative tree cover threshold from the formal forest definition to the total area of forest land-use at feature-level, e.g., it is assumed that for a threshold of 50%, 10000m² of forest land-use provide an effective tree cover of 5000m².

Tool inputs

Table 28. COIN (Total tree cover) input data sources and tool parameters.

Data or Parameter	Data Type	Description
User-defined active layer	Polygon feature layer	Layer defined as active layer, and that contains distinct patch geometries, and with derived properties (traits) at feature-level (per polygon, plot), as derived, e.g., by SITA.
Forest relative tree cover threshold	Double	Relative tree cover threshold that must be met or exceeded, according to the formal definition of forest and treed area (Scheuer et al., 2022).
Ancillary Data	Polygon feature layer	Optional. Ancillary data layers may be defined as needed to represent the following supported entities: Forest.

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Tool outputs

The user-defined active layer is augmented with the following fields.

Table 29. COIN (Total tree cover) fields.

Field	Description
TOTAL_TREE_COVER_AREA	Estimated tree cover (in ha).

Limitations

- Uncertainties are inherent to the estimation of tree cover from total area with forest land-use/land cover.

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Street tree density

Determines overall street tree density (in number of trees/km), e.g., as suggested by Bundesamt für Naturschutz (2023) as basic indicator. The assessment is based on the TOPOMOD Modelling of spatial relationships and topology-provided classified tree cadastre. Values reported include street tree density for potential street trees (i.e., trees classified as IN_STREET = 1), as well as street tree density additionally considering likely near/adjacent trees, i.e., classified as ADJ_STREET = 1). Street length in km is determined from length of individual line segments from the street centerlines layer.

Tool inputs

Table 30. COIN (Street tree density) input data sources and tool parameters.

Data or Parameter	Data Type	Description
Classified tree cadastral data	Point feature layer	This dataset is generated by TOPOMOD.
Streets	Line feature layer	Street centerlines.

Tool outputs

Reported are overall street tree densities considering (i) only potential street trees; and (ii) potential street trees and likely near trees/trees adjacent to streets.

Limitations

- Uncertainties are inherent to the estimation of street trees and trees near/adjacent to street entities. These uncertainties are propagated to the estimation of street tree density.

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Total forest cover

Plot-dependent forest cover identification (top-down)

COIN “Plot-dependent forest cover identification” seeks to identify/locate patches of forest cover. The function identifies forest entities at the (plot/patches) feature level. Therefore, first, following Scheuer et al. (2022), forests are defined as treed area entities with a minimum area of 0.5ha. Treed areas, in turn, are defined as areas with a minimum relative tree cover, by default 50%. Second, with the forest definition relying on total and subsequently relative tree cover, tree cover is estimated at the feature level. This estimation follows the rules as outlined in COIN Total Tree cover (see above). Subsequently, third, based on feature area and relative tree cover, plots/patches are classified as treed area or forest, when defining relative tree cover and area thresholds are met at the feature level. Additionally, total forest area at dataset level is determined.

For forests included as ancillary data, forest land-use is first converted into potential tree cover (based on assumed relative tree cover of forest). This becomes particularly relevant if plots are only covered partially by forest, but also by (e.g., TCAC-modelled) tree cover features. By assuming tree cover from forest area, total tree cover may be estimated at the feature level.

Tool inputs

Table 31. COIN (Plot-dependent forest cover) input layers and parameters.

Data or Parameter	Data Type	Description
User-defined active layer	Polygon feature layer	Layer defined as active layer, and that contains distinct patch geometries, and with derived properties (traits) at feature-level (per polygon, plot), as derived, e.g., by SITA.
Forest relative tree cover threshold	Double	Relative tree cover threshold that must be met or exceeded, according to the formal definition of forest and treed area (Scheuer et al., 2022).
Ancillary Data	Polygon feature layer	Optional. Ancillary data layers may be defined as needed to represent the following supported entities: Forest.

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Tool outputs

The user-defined active layer is augmented with the following fields.

Table 32. COIN (Plot-dependent forest cover) fields.

Field	Description
IS_TREEDAREA	Boolean value indicating classification of a plot (polygon feature) as treed area. A value of 1 indicates a treed area (i.e., a plot/feature with ≥ forest relative tree cover threshold)
IS_FOREST	Boolean value indicating classification of a plot (polygon feature) as a forest area. A value of 1 indicated forest (i.e., treed area and plot/feature size ≥ 5000m²).
TOTAL_FOREST_AREA	The area (in ha) counted towards total forest cover. This corresponds to the total area of plots that are classified as forest.

Limitations

- The dependence on plot traits, e.g., area, to result in a forest patch in accordance with the underlying formal definition, results in a dependency on actual plot delineations. I.e., the geometry of plots/the chosen active layer may significantly affect/and/or hinder the identification of forests.
- Uncertainties are inherent to the estimation of tree cover from total area with forest land-use/land cover.

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Geometry-driven forest identification (bottom-up)

To avoid a dependency on feature (plot/patch) geometries in the classification of potential forest entities, SIAC proposes a geometry-driven identification of forests. This approach is based on the spatial-topological relationships of tree cover features themselves. More specifically, tree cover features considered as being spatially related with each other are considered to potentially form an individual forest stand. Here, a spatial relationship is assumed if the oriented minimum bounding rectangle of tree cover features intersect each other.

As specified by the user in form of a near threshold, tree cover may be spatially related not only in case of immediate overlaps or adjacency of their oriented minimum bounding rectangles, but also when tree cover is located in close proximity. Consequently, the oriented minimum bounding rectangles are buffered (using near threshold as buffer radius) to consider other near features. Overlapping/intersecting oriented minimum bounding rectangles are subsequently dissolved. Then, the dissolved oriented minimum bounding rectangles form the geometric basis for the identification of forest patches. I.e., total and relative tree cover is determined for each dissolved oriented minimum bounding rectangles, and the formal definition of forest applied to identify treed areas and forest stands, analogous to the COIN "Plot-dependent forest cover identification" tool.

Tool inputs

Table 33. COIN (Geometry-driven forest cover identification) input layers and parameters.

Data or Parameter	Data Type	Description
Tree Cover	Polygon feature layer	This dataset is generated by TCAC. Alternatively, another polygon feature layer may be provided.
Forest relative tree cover threshold	Double	Relative tree cover threshold that must be met or exceeded, according to the formal definition of forest and treed area (Scheuer et al., 2022).
Near threshold	Double	Threshold indicating distance (in m) until which near proximity is assumed and other tree cover features considered.

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Tool outputs

Table 34. COIN (Geometry-driven forest cover identification) outputs.

Data or Parameter	Data Type	Description
Tree Cover Oriented Minimum Bounding Rectangles	Polygon feature layer	Modelled oriented minimum bounding rectangle features for tree cover layer, with tree cover buffered by user-specified near threshold.

Table 35. COIN (Geometry-driven forest cover identification) fields.

Field	Description
TREE_COVER_AREA	Tree cover (in m²) for a given oriented minimum bounding rectangles-derived feature.
TREE_COVER_SHARE	Relative tree cover, i.e., share of tree cover for a given oriented minimum bounding rectangles-derived feature.
IS_TREEDAREA	Boolean value indicating classification of a plot (polygon feature) as treed area. A value of 1 indicates a treed area (i.e., a plot/feature with ≥ forest relative tree cover threshold)
IS_FOREST	Boolean value indicating classification of a plot (polygon feature) as a forest area. A value of 1 indicated forest (i.e., treed area and plot/feature size ≥ 5000m²).
TOTAL_FOREST_AREA	The area (in ha) counted towards total forest cover. This corresponds to the total area of plots that are classified as forest.

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Carbon Sequestration and Storage

Determine the average amount of carbon stored, or sequestered annually, respectively, as a function of tree cover area (in m²). If forest has been defined as ancillary class for the assessment of traits by SITA, then total forest cover at the spatial analysis unit level is being considered by COIN "Regulation of air quality". Tree cover is estimated from forest area based on the forest relative tree cover threshold.

Tool inputs

Table 36. COIN (Carbon sequestration and storage) input layers and parameters.

Data or Parameter	Data Type	Description
User-defined active layer	Polygon feature layer	Layer defined as active layer, and that contains distinct patch geometries, and with derived properties (traits) at feature-level (per polygon, plot), as derived, e.g., by SITA.
Average Carbon Sequestration Rate	Double	Average carbon sequestration rate in kg C per m² of tree cover. By default, a value of 0.28 kg C m^{-2} is used, based on (Nowak et al., 2013).
Average Carbon Storage Rate	Double	Average carbon storage rate in kg C per m² of tree cover. By default, a value of 7.69 kg C m^{-2} is used, based on (Nowak et al., 2013).
Forest relative tree cover threshold	Double	Relative tree cover threshold that must be met or exceeded, according to the formal definition of forest and treed area (Scheuer et al., 2022).

Tool outputs

The user-defined active layer is augmented with the following fields. In addition, the total carbon stored (in Mg C), and total carbon sequestration (in Mg C per year) is reported.

Table 37. COIN (Carbon sequestration and storage) fields.

Field	Description
AVG_C_SEQSTR	Average carbon sequestration (in kg C per year) for a given patch.
AVG_C_STORE	Average carbon storage (in kg C) for a given patch.

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Limitations

- The assessment is based only on ecosystem service potentials/rates. Benefits are determined based on this rate and total tree cover.
- Uncertainties are inherent to the estimation of tree cover from total area with forest land-use/land cover.

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Regulation of air quality

Determine the contribution of tree cover to the regulation of air quality by removal of air pollutants SO_2, NO_2, O_3, CO, and PM_{10}i.e., as a function of tree cover area (in m²). If forest has been defined as ancillary class for the assessment of traits by SITA, then total forest cover at the spatial analysis unit level is being considered by COIN "Regulation of air quality". Tree cover is estimated from forest area based on the forest relative tree cover threshold.

Tool inputs

Table 38. COIN (Regulation of air quality) input layers and parameters.

Data or Parameter	Data Type	Description
User-defined active layer	Polygon feature layer	Layer defined as active layer, and that contains distinct patch geometries, and with derived properties (traits) at feature-level (per polygon, plot), as derived, e.g., by SITA.
SO_2 removal rate	Double	Pollutant removal rate in in g per m² of tree cover and year. By default, a value of 1.32 g m^{-2} a^{-1} is used, based on Kremer et al. (2016).
NO_2 removal rate	Double	Pollutant removal rate in in g per m² of tree cover and year. By default, a value of 2.54 g m^{-2} a^{-1} is used, based on Kremer et al. (2016).
PM_{10} removal rate	Double	Pollutant removal rate in in g per m² of tree cover and year. By default, a value of 2.73 g m^{-2} a^{-1} is used, based on Kremer et al. (2016).
O_3 removal rate	Double	Pollutant removal rate in in g per m² of tree cover and year. By default, a value of 3.06 g m^{-2} a^{-1} is used, based on Kremer et al. (2016).
CO removal rate	Double	Pollutant removal rate in in g per m² of tree cover and year. By default, a value of 0.58 g m^{-2} a^{-1} is used, based on Kremer et al. (2016).
Forest relative tree cover threshold	Double	Relative tree cover threshold that must be met or exceeded, according to the formal definition of forest and treed area (Scheuer et al., 2022).

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Tool outputs

The user-defined active layer is augmented with the following fields. In addition, the total amount of each pollutant removed (in Mg per year) is reported.

Table 39. COIN (Regulation of air quality) fields.

Field	Description
TOT_SO2	Total SO2 removed (in g per year) by a given patch.
TOT_NO2	Total NO2 removed (in g per year) by a given patch.
TOT_PM10	Total PM10 removed (in g per year) by a given patch.
TOT_O3	Total O3 removed (in g per year) by a given patch.
TOT_CO	Total CO removed (in g per year) by a given patch.

Limitations

- The assessment is based only on ecosystem service potentials/rates. Benefits are determined based on this rate and total tree cover.
- Uncertainties are inherent to the estimation of tree cover from total area with forest land-use/land cover.

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Local OLS Regression

Local Ordinary Least-Squares (OLS) Regression computes a linear regression function that uses SITA-assessed traits as predictors, and that uses a point feature layer holding values as target layer (dependent variable). The tool may be applied to assess any type of relationship between local traits and a dependent variable, however, a prominent use case is the assessment of the relationship between local traits, particularly tree cover, and land surface temperature as a proxy for air temperature and thus, impacts of tree cover and tree-based entities on cooling.

The function consumes a SITA-assessed polygon feature layer (i.e., a layer with relevant fields providing total/relative cover of distinct entity types, that is set as active layer), then extracts values from a point feature layer to each patch of the active layer (i.e., here, typically land surface temperature), and subsequently computes a multiple ordinary least-squares regression to assess the relationships of patch-level traits (used as independent variables) with point feature values averaged at the patch level (i.e., here, mean land surface temperature) as dependent variable.

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Tool inputs

Table 40. COIN (Local OLS regression) input layers and parameters.

Data or Parameter	Data Type	Description
User-defined active layer	Polygon feature layer	Layer defined as active layer, and that contains distinct patch geometries. SITA will assess properties (traits) for each distinct patch (polygon, plot) in this layer.
User-defined target layer	Point feature layer	Layer holding dependent variable values (e.g., land surface temperature) in a field named 'VALUE. This layer is set in the tool parameters.
Cover Type		Determines whether total area of cover is used as predictor, or relative cover.
Predictors		Determines variables included as predictors. One of the following options: "Include impervious cover as single entity" includes either total or relative impervious cover in the regression. Impervious cover is the sum of street and building cover. "Include impervious cover as individual entities" includes total or relative cover of streets and buildings as separate predictors in the regression model. "Exclude impervious cover" excludes the total or relative cover by streets and/or buildings from the regression.
Include supported ancillary types as predictors		If checked, total or relative cover of supported ancillary classes will be included as predictors in the regression model. Supported entities include forest, water bodies, and urban green space, as polygon-type ancillary data.
Include locally weighted linear regression		If enabled, will include a nonparametric locally weighted linear regression in addition to linear ordinary least squares regression model in plots.

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Tool outputs

The user-defined base layer is augmented by the fields shown in the following table.

Table 41. COIN (Local OLS regression) fields.

Field	Description
MEAN_VAL	Mean of dependent variable value (in given unit) at patch level (e.g., land surface temperature).
MIN_VAL	Minimum observed dependent variable value (in given unit) in given patch (e.g., land surface temperature).
MAX_VAL	Maximum observed dependent variable value (in given unit) in given patch (e.g., land surface temperature).
STD_VAL	Standard deviation of dependent variable value (in given unit) in given patch (e.g., land surface temperature).
EST_IMPACT	Estimated impact on dependent variable (in given unit) at patch level (e.g., land surface temperature). This value is computed as sum of independent variable's values multiplied by estimated regression coefficients $(a_1x_1) + (a_2x_2) + \ldots + (a_ix_i)$

The regression model is summarized in the tool log. In addition, for each pair of independent variable and dependent variable, an OLS linear regression plot is returned.

Limitations

- Spatial resolution of land surface temperature layer determines accuracy of the assessment. Depending on this resolution and size of features in the corresponding active layer, no points from the land surface temperature layer may intersect active layer patch features, thus resulting in NULL values written as extracted temperature.
- Linear relationship between predictors and dependent variable is assumed, as a linear regression model is used. However, assumption of a linear relationship is not necessarily true. Use of alternative regression models is not supported at this time.
- The regression model is currently including all values, i.e., including possible outliers.
- The EST_IMPACT field should be interpreted with care. Computed values are strongly influenced by the coefficient of determination and other metrics of the regression model. The value may severely overestimate impacts.

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Pre-Processing of data

Modelling of street morphology

SIAC's pre-processing module permits modelling of street morphology from street centrelines and buildings as inputs. The function is based on momepy's StreetProfile function (Fleischmann, 2019). Therefore, momepy determines a profile of street segments, including mean width, as a function of constraints (i.e., buildings) or maximum tick length, i.e., the assumed maximum buffer distance from the street centerline, if no constraint has been identified. Thereby, a polygonal representation of the streetscape is approximated from street centerlines.

Tool inputs

Table 42.Pre-processing (Modelling of street morphology) input layers and parameters.

Data or Parameter	Data Type	Description
Street centerlines	Line feature layer	Centerlines of streets.
Building footprints	Polygon feature layer	Building geometry/footprint.
Maximum tick length	Double	Assumed maximum road width from street centerline if no constraining factor (building) is found.

Tool outputs

Table 43. Pre-processing (Modelling of street morphology) outputs.

Data or Parameter	Data Type	Description
Street morphology	Polygon feature layer	Modelled street morphology derived from street centerlines, buildings, and assumed maximum tick length.

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Limitations

- The tool requires assuming a maximum tick length.
- True street morphology is the better represented, the better centerlines are constrained within maximum tick length. Highly variable building distances to street centerlines may result in over- or underestimation of average street width that is used for buffering.

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Modelling of Plots using Enclosed Tessellation

The modelling of plots, based on enclosed tessellation provided by momepy (Fleischmann, 2019), is a means to derive spatial analysis units that resemble (but are not necessarily identical to) plots.

Tool inputs

Table 44. Pre-processing (Modelling of plots using Enclosed Tessellation) input layers and parameters.

Data or Parameter	Data Type	Description
Street centerlines	Line feature layer	Centerlines of streets.
Building footprints	Polygon feature layer	Building geometry/footprint.

Tool outputs

Table 45. Pre-processing (Modelling of plots using Enclosed Tessellation) outputs.

Data or Parameter	Data Type	Description
Enclosed Tessellation	Polygon feature layer	Modelled plots.

Limitations

- Plots modelled by enclosed tessellation do not imply cadastre conformity and may not be suitable to model property relationships or modes of access.
- At the boundary of data layers, a maximum distance threshold is used for constructing tessellation units. This may cause edge effects and may not properly consider relevant features across input layers.

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