



Standard use of Geographic Information System (GIS) techniques in honey bee research

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To cite this article: Stephanie R Rogers & Benno Staub (2013) Standard use of Geographic Information System (GIS) techniques in honey bee research, Journal of Apicultural Research, 52:4, 1-48

To link to this article: <http://dx.doi.org/10.3896/IBRA.1.52.4.08>



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REVIEW ARTICLE



Standard use of Geographic Information System (GIS) techniques in honey bee research

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Received 4 January 2013, accepted subject to revision 11 February 2013, accepted for publication 11 March 2013.

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Summary

Geographic Information Systems (GIS) have been used in various fields and disciplines to summarize and analyse spatial patterns and distributions, for the purpose of understanding how geographic and non-geographic entities interact with each other over space and time. Although honey bees are directly related to and influenced by their local environment, few studies have incorporated honey bee data into GIS for the purposes of gauging these spatial relationships. This paper will briefly discuss some of the types of spatial analyses and GIS methods that have been used for bees, and also, how some methodologies developed in the non-*Apis* bee domain could be applied to honey bee research. With this paper, we aim to stimulate spatial thinking processes and thus the future use of GIS analyses to better understand the relationships between environmental characteristics and honey bee health and abundance. We will introduce the framework and some important basic concepts of GIS, as well as provide detailed instructions for becoming familiar and comfortable in using the GIS softwares ArcGIS and Quantum GIS (QGIS) (a commercial and free GIS package) for the basics of geospatial research.

Uso estándar de las técnicas de Sistemas de Información Geográfica (SIG) en la investigación de la abeja de la miel

Resumen

Los Sistemas de Información Geográfica (SIG) se han utilizado en diversos campos y disciplinas para resumir y analizar los patrones y distribuciones espaciales, con el fin de entender cómo las entidades geográficas y no geográficas interactúan entre sí en el espacio y en el tiempo. Aunque las abejas melíferas están directamente relacionadas e influidas por su ambiente local, pocos estudios han incluido estos datos en los SIG para analizar estas relaciones espaciales. Este artículo discutirá brevemente algunos de los tipos de análisis espaciales y métodos de SIG que se han utilizado para las abejas, así como también, algunas metodologías desarrolladas en dominios no-*Apis* que podrían ser aplicadas a la investigación de la abeja de la miel. El objetivo de este trabajo es fomentar los procesos de pensamiento espacial y por lo tanto el futuro uso de los análisis SIG para entender mejor las relaciones entre las características ambientales con la salud de las abejas melíferas y con la abundancia de estas. Vamos a introducir el marco y algunos conceptos básicos importantes de los SIG, así como proporcionar instrucciones detalladas para familiarizar y facilitar el uso de los programas SIG, ArcGIS y Quantum GIS (QGIS) (un paquete SIG comercial y libre) para los fundamentos de la investigación geoespacial.

Footnote: Please cite this paper as: ROGERS, S R; STAUB, B (2013) Standard use of Geographic Information System (GIS) techniques in honey bee research. In V Dietemann; J D Ellis; P Neumann (Eds) *The COLOSS BEEBOOK, Volume I: standard methods for Apis mellifera research*. Journal of Apicultural Research 52(4): <http://dx.doi.org/10.3896/IBRA.1.52.4.08>

NOTE: Figures prefixed by "S" are contained in the Online Supplementary Material to be found at http://www.ibra.org.uk/downloads/20130812_23/download

地理信息系统技术在蜜蜂研究中的标准应用

摘要

为了理解地理和非地理的实体之间如何在空间和时间上互作，地理信息系统（GIS）已被用于多种领域和学科以概括和分析空间模式和分布。尽管蜜蜂与它们的生活区域环境直接相关并受其影响，但很少有研究将蜜蜂的数据与GIS结合起来测定这些空间关系。本文将简要讨论已用于蜜蜂的一些类型的空间分析和GIS方法，以及如何将一些在非蜜蜂领域发展起来的方法应用于蜜蜂研究。通过本文，我们意图刺激空间思考的进程，从而实现未来通过GIS分析来更好的理解环境特征与蜜蜂健康和丰富度的关系。我们将介绍GIS的框架和一些重要的基本概念，同时提供GIS软件ArcGIS和Quantum GIS（两者分别是商业化和免费的GIS包）详细的使用说明，使人们熟悉并轻松地使用以作为地理空间研究的基础。

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1. Introduction

Due to the close relationship between honey bees and their surroundings, and because of recent increases in colony mortality in many regions of the world (Carreck and Neumann, 2010; Williams *et*

al., 2010), there is an urgent need to better understand how environmental changes affect habitat, life patterns, and the overall health of honey bees. This type of research can be facilitated through the use of Geographic Information Systems (GIS), which can briefly be described as a software system for handling and analysing map

Table 1. Publication names, authors, and websites of free GIS Books and information sources.

Name of publication	Author(s), year	Website
Map Projections: A Working Manual	Snyder, 1987	http://pubs.er.usgs.gov/publication/pp1395
Geospatial Analysis - A comprehensive guide	De Smith, Goodchild, and Longley, 2007	http://www.spatialanalysisonline.com
A Practical Guide to Geostatistical Mapping	Hengl, 2009	http://www.lulu.com/shop/tomislav-hengl/a-practical-guide-to-geostatistical-mapping/ebook/product-17389015.html
GIS Commons: An Introductory Textbook on Geographic Information Systems	Schmandt, 2009	http://giscommons.org/
Various ESRI E-books	Many	http://www.esri.com/industries/ebooks

data through the use of coordinate systems and georeferenced information to aid in the analysis of spatial patterns that may exist between entities on the Earth's surface (Burrough and McDonnell, 1998). Because of its broad application, GIS methods are used in a diverse array of disciplines, including geoscience (Bonham-Carter, 1994), economics (Pogodzinski and Kos, 2012), and biology (Kozak *et al.*, 2008). For example, GIS has been used extensively to undertake spatial analyses of the effects of land-use and climate change on declines of native bee abundance and health (Arthur *et al.*, 2010; Biesmeijer *et al.*, 2006; Chifflet *et al.*, 2011; Choi *et al.*, 2012; Fitzpatrick *et al.*, 2007; Giannini *et al.*, 2012; Kremen, 2002; Kremen *et al.*, 2004; Watson *et al.*, 2011; Williams *et al.*, 2012).

Through the use of spatial analyses, researchers using GIS were able to determine that native bees were more efficient crop pollinators when access to nearby forests was provided (Arthur *et al.*, 2010; Kremen *et al.*, 2004; Watson *et al.*, 2011). Additionally, relationships between climate and native bee species richness and abundance have been identified using GIS modelling procedures (Giannini *et al.*, 2012). For honey bees, GIS analyses have been incorporated into relatively few research initiatives (Berardinelli and Vedova, 2004; Naug, 2009; Henry *et al.*, 2012). With this paper, we aim to stimulate spatial thinking processes and thus the future use of GIS analyses to better understand the relationships between environmental characteristics and honey bee health and abundance for a broader geographic overview of the mechanisms affecting their plight (Naug, 2009). In this paper, we introduce the framework and some important basic concepts of GIS, and provide detailed instructions about using the GIS softwares ArcGIS and Quantum GIS (QGIS) for the geospatial study of honey bees. We hope that the knowledge gained from this paper will further the field of honey bee science, but also promote the use of GIS in other fields of study.

2. What is GIS?

2.1. Definition

Geographical Information Systems (GIS) are computer systems based on hardware, software, and georeferenced data that can be used to collect, store, manage, process, analyse, and visualize both spatial and non-spatial information representing real-world geographic

phenomena (Burrough and McDonnell, 1998; Neteler and Mitasova, 2008). Georeferenced data refers to any data that are linked to a location on the Earth's surface through the use of a geographic or projected coordinate system. GIS data are digital objects which represent real-world entities (Longley *et al.*, 1999) and are defined by: their geometric properties (spatial location), their attributes (characteristics associated with each object), and their topology (definition of how entities are related to others in space) (Burrough and McDonnell, 1998). In other words, data provide means to locate them in space and can be overlaid, calculated, manipulated, visualised and analysed along with other data layers that use the same coordinate system. Each entity in the real world is represented by a data layer with geometric and topologic properties and an associated set of attributes, in the form of a table, which define the characteristics of that entity. GIS facilitates the analysis of spatial relationships within datasets based on the topological properties within the data. Topology refers to the interconnectivity and interrelated properties between data and defines and describes how spatial objects relate to their neighbours in space. This geographic descriptor is what sets GIS data apart from other data types (Burrough and McDonnell, 1998) (for a list of free GIS books and other information sources see Table 1).

2.2. GIS framework

The main principles of GIS (geometric properties, attributes, and topology) are built into two data structures: vector (e.g. points, lines, and polygons) and raster (e.g. climatic, altitude, or satellite imagery). The terms "layer" or "dataset" are used to denote a raster or a vector file type that contains a similar theme, for example, varying elevations across a terrain or locations of honey bee colonies, respectively. It is possible to convert a raster layer to a vector layer and vice versa, depending on what type of analysis will be conducted with the data. Each layer contains information about its geometric properties and a table of attributes associated to and linked with, its respective geometric properties (Fig. 1). You can view each layer's properties in GIS to see the resolution, file type, size of the file, and other information of importance.

2.2.1. Vector data structure

Vector layers represent discrete features in space in the forms of points, lines, and polygons. They represent unchanging static entities

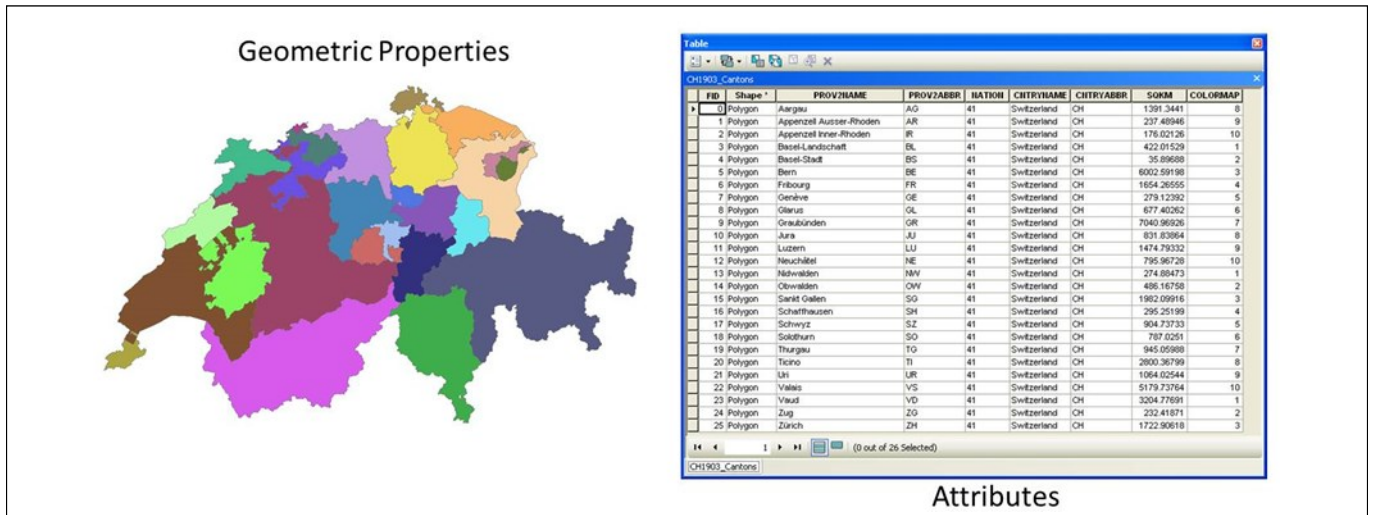


Fig. 1. The GIS data framework is made up of both geometric properties and attributes associated with the geometry. A row in the attribute table exists for every polygon on the map. Some of the attributes for this Swiss layer include the names of cantons and their abbreviations, the country code, the country name and abbreviation, and the area. Reproduced with permission of Swisstopo (BA13016).

and do not contain spatial or temporal information (Burrough and McDonnell, 1998). For example, a polygon layer could represent the extent of an apiary, and a point layer could represent a honey bee colony on a map. Line layers can represent rivers, roads, tracks, and any other linear features. In Fig. 2 a polygon, point, and line layer are shown as examples.



Fig. 2. A map displaying a point, lines, and polygons. Reproduced with permission of Swisstopo (BA13016).

2.2.2. Raster data structure

Raster layers represent continuous features such as aerial and satellite imagery, as well as Digital Elevation Models (DEM), which store elevation data across a surface (see section 3.2.4. for more information). The value of each pixel of a thematic raster layer represents the attribute value. For satellite imagery, pixel values represent physical values of surface reflectances and for terrain-model

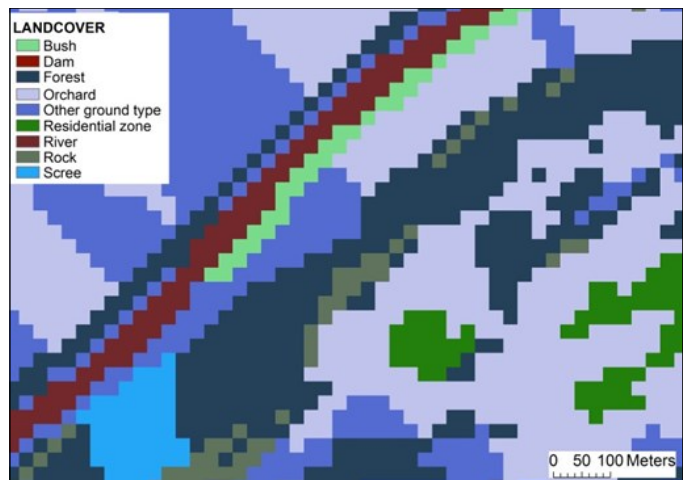


Fig. 3. A map displaying the raster data structure of a landcover layer which was converted from vector format. The legend denotes the landcover properties which are displayed. Reproduced with permission of Swisstopo (BA13016).

data pixel values represent absolute topographic heights (Campbell, 2002). For example, if the resolution of the image is 25 m, then each 25 m pixel in the image will be representative of the average value of that 25 m on the ground. In Fig. 3, a land cover vector layer was transformed to a raster to visualize the pixel differences and value types.

2.3. GIS functionalities

The main functionalities of GIS include interfaces for database management, geoprocessing and spatial analysis, as well as visualisation and map creation. Here, these functionalities are introduced and the specific tools will be discussed more in-depth in further sections.

2.3.1. Database management

A GIS database is used to store, create, organize, manipulate, and query spatial and their linked non-spatial datasets (Burrough and McDonnell, 1998). GIS facilitates the link between geographic and non-geographic data and enables the comparison and assessment of various data types (Rigaux *et al.*, 2002). Compared to traditional (non-spatial) databases (e.g. those without geographic coordinates), geographic databases make explicit locational distinctions for each dataset stored in the database, that is, all geographic information is linked to a location on the earth's surface through coordinates (Arctur and Zeiler, 2004).

2.3.2. Geoprocessing and spatial analysis

GIS can be used to calculate, analyse, and manipulate spatial data to examine spatial relationships and to create new data (De Smith *et al.*, 2007). Basic manipulations of geographic datasets such as extracting new information from existing layers or clipping specific geographic extents can be referred to as geoprocessing. Geoprocessing refers to the process of creating a new geographic data layer after the calculation of an input layer(s) (Wade and Sommer, 2006).

Spatial analysis is a central concept in GIS and refers to more complex calculations which have been developed from various quantitative methodologies outside of GIS and incorporated into GIS over time (Longley *et al.*, 1999; Conolly and Lake, 2006; De Smith *et al.*, 2007). Spatial analyses can be used to summarize and analyse the spatial properties of geographic distributions, to solve spatial problems through modelling, and finally, to aid in spatial decision making (Longley *et al.*, 1999). Because this is a basic introduction to GIS, we will focus more on the geoprocessing aspects of GIS and touch briefly on more complex spatial analyses.

2.3.3. Data visualisation and map creation

One of the main benefits of GIS is that it gives researchers the ability to visualize their data in a variety of formats, which enables the creation of new links and relationships between spatial entities while discovering spatial interactions that were perhaps unknown before. GIS is also a common cartographic platform which facilitates the production of maps, either to present a geographic area or the results of data analysis using spatial data. The results of GIS analysis can be displayed as maps using a variety of symbolisations and annotation features as the final step in a GIS investigation.

3. Geographic data

GIS data represent real-world phenomena based on their geometric properties, attributes, and topology (Burrough and McDonnell, 1998).

3.1. File types and extensions

Often, GIS software has its own file types for vector and raster data. For example, the Environmental Systems Research Institute's (ESRI) commercial ArcGIS software most commonly uses shapefiles for vector data and grids for raster data. Shapefiles and grids have come to be some of the most commonly known GIS formats and can often be read by and incorporated into other GIS programs without the need for conversion, as is the case for Quantum GIS (QGIS). It is important to note that most layers are made up of multiple files with different file extensions. For example, a shapefile may look like a single file in the GIS, but actually, it is composed of multiple file extensions. It is detrimental to the data layer if one of these extensions gets lost or deleted. Some of the extensions often associated with shapefiles are: *.shp (required file that stores the feature geometry), *.shx (required file that stores the index of the feature geometry), *.dbf (database table that stores the attribute information) or *.prj (file that stores the coordinate system information). The entire list of extensions can be found by searching "shapefile file extensions" in the ArcGIS help menu (<http://resources.arcgis.com/en/help/main/10.1/>).

Multiple raster dataset file formats including ASCII (*.asc), GeoTiff (*.tif), JPEG (*.jpg), and GIFs (*.gif), to name only a few, can be supported in most GIS software. Again it is important to keep all files when copying and moving data. For example, a Geotiff file often comes with two files, *.tif and *.tfw. The *.tif holds the image, and the *.tfw holds the information about the georeference.

3.2. Common GIS data types

The geometric aspect associated with GIS data is what separates geographic databases from other databases (Burrough and McDonnell, 1998). Geographic databases are sometimes referred to as geodatabases, which refer to databases specific to geographic data. Until recently, most GIS data were generated and distributed by government or private industries and had to be purchased. Now, there are many sources for downloading free data (Table 2). The amount of available data largely depends on the area of interest, as urban areas tend to have more data available than rural or remote areas. Another important aspect of geographic data is the metadata. Metadata are the information provided about the data, thus, data about data (Burrough and McDonnell, 1998). When downloading data online or receiving data from an outside source, metadata are important for obtaining knowledge about when the data were created, for what purpose, by whom, and using which coordinate system, among other things. Without this information, data would be of limited use only. In the following section we will introduce some of the common file formats and extensions, as well as some geographic

Table 2. Names, websites, and types of data available from various free data sources.

Name	Website	Types of data
Aster GDEM	http://asterweb.jpl.nasa.gov/gdem.asp	30 m DEM of the world
CloudMade	downloads.cloudmade.com	Layers created from Open Street Maps for various places in the world
Corine Land Cover 2006 (European Environment Agency (EEA))	http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2	Land cover raster data for Europe 100 m and 250 m resolutions
European Environment Agency (EEA)	http://www.eea.europa.eu/data-and-maps/data#c5=all&b_start=0&c9=CLC2006	Land use, economics, natural resources, water, etc.
FOSSGIS (Free and Open Source Software for GIS)	http://freegis.org/	Many from multiple sources
Global Land Cover Facility (GLCF)	Glc.f.umd.edu/data/	Satellite imagery, products derived from satellite imagery, vector products
Open Street Map	www.openstreetmap.org	Global or individual country or state map data
Swisstopo Landsat Image	http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/images/ortho/landsat.html	Digital satellite mosaic
United Nations Geographic Information Working Group (UNGWIG) Second Administrative Level Boundaries (SALB)	http://www.unsalb.org/	International borders
United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center	http://eros.usgs.gov/#/Find_Data	Aerial Photography Satellite Imagery Elevation Land Cover Digitized Maps Image Gallery Collections

data examples. The possibilities of types of data in GIS are becoming broader as the technology develops. The following is a non-exhaustive list that shows some of the data types you may encounter when using GIS.

3.2.1. Maps

Topographic maps (Fig. 4) are representations of the terrain which include both natural and man-made features, including, relief (in the form of contour lines), towns, villages, roads, and other geographic characteristics (Burrough and McDonnell, 1998). They are those maps which people are most familiar with. In GIS, topographic maps are stored in raster format in their entirety, but can also be broken down into their respective categories (rivers, buildings, roads, etc.) in vector layers.

3.2.2. Aerial imagery

Photos taken from the air, usually from an aircraft, are referred to as aerial imagery or photographs (Fig. 5). These images provide valuable information about landscape changes by comparing photos over time. When aerial images are georeferenced, i.e. located with respect to a geographic or projected coordinate system, they can be used as raster layers in GIS (Burrough and McDonnell, 1998). The different types of aerial images include black and white, true colour, panchromatic, and infrared and can each be used for different purposes (Campbell, 2002).



Fig. 4. A sample topographic map (scale 1: 200 000) covering the study area of Fribourg, Switzerland. This map comes from Swisstopo (2013) and must only be used for visualization purposes in this paper. Reproduced with permission of Swisstopo (BA13016).

3.2.3. Satellite imagery

Satellite images are those that have been taken from satellites. Landsat (Fig. 6) is one of the longest running platforms for image acquisition using the Thematic Mapper (TM) or the Enhanced



Fig. 5. A sample orthophoto, with a resolution of 50 cm, showing the study area of Fribourg, Switzerland. This photo comes from Swisstopo (2013) and must only be used for visualization purposes in this paper. Reproduced with permission of Swisstopo (BA13016).



Fig. 6. A section of the Swisstopo (2013) Landsat image (freely available from at <http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/images/ortho/landsat.html>) with a resolution of 25m, covering the study area of Fribourg, Switzerland. Reproduced with permission of Swisstopo (BA13016).

Thematic Mapper (ETM) satellite image acquisition systems (<http://landsat.gsfc.nasa.gov/>) which provide multispectral imagery for the whole world (Campbell, 2002). Satellite imagery is often expensive to buy as the equipment is difficult to operate and maintain, but conveniently, Landsat and other satellite images can be added as raster layers directly into the GIS interface.

3.2.4. Digital Elevation Model (DEM)

A DEM (Fig. 7) is a raster dataset that represents the altitude of the terrain. Depending on the resolution of the image, each pixel represents the average altitude of the terrain covered by that pixel. For example, if the image resolution is 30 m, the altitude of the terrain on the ground that is covered by that pixel within that 30 m square is averaged and the value is assigned to that pixel.

With a DEM, numerous calculations can be performed including the calculation of slope (in degrees or percent) of the terrain, the direction each slope is facing (aspect), and where shadows exist when the sun is hitting the terrain from a certain angle (hillshade). A DEM is also the base dataset for calculations of solar radiation, hydrographic, and various modelling calculations.

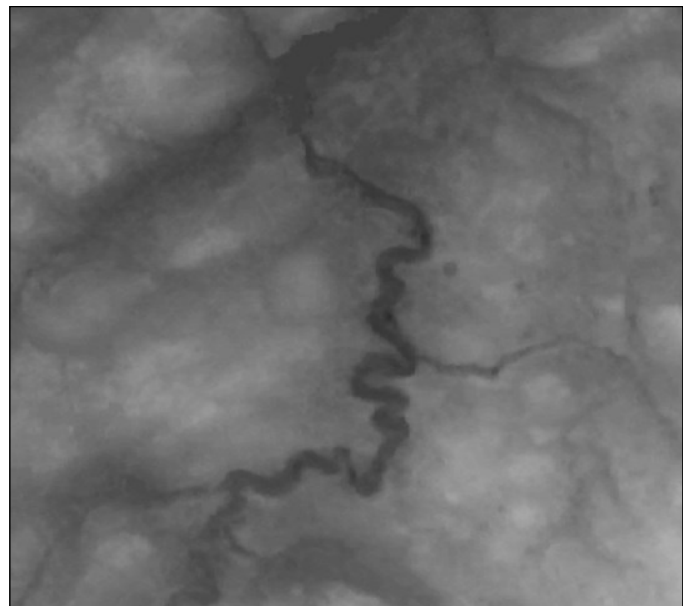


Fig. 7. A sample Digital Elevation Model (DEM) (30 m resolution) covering the study area of Fribourg, Switzerland. This map was a free download from ASTER GDEM which was projected to the Swiss projected coordinate system (CH1903 LV03).

3.2.5. Thematic vector data

Vector (Fig. 2) data represent a broad range of information, as they include all layers represented by points, lines, or polygons. In a GIS database, common vector layers might represent administrative boundaries (the locations of countries, provinces, states, cantons, etc.), hydrography (rivers, dams, lakes, etc.), built-up areas (buildings, stations, airports, etc.), and land cover.

4. Coordinate systems

This section will briefly introduce the concept of coordinate systems in GIS. For any analysis, it is important to know the coordinate system of the data which represent the study area (region of interest) and to ensure that all of your data layers are already in, or can be converted

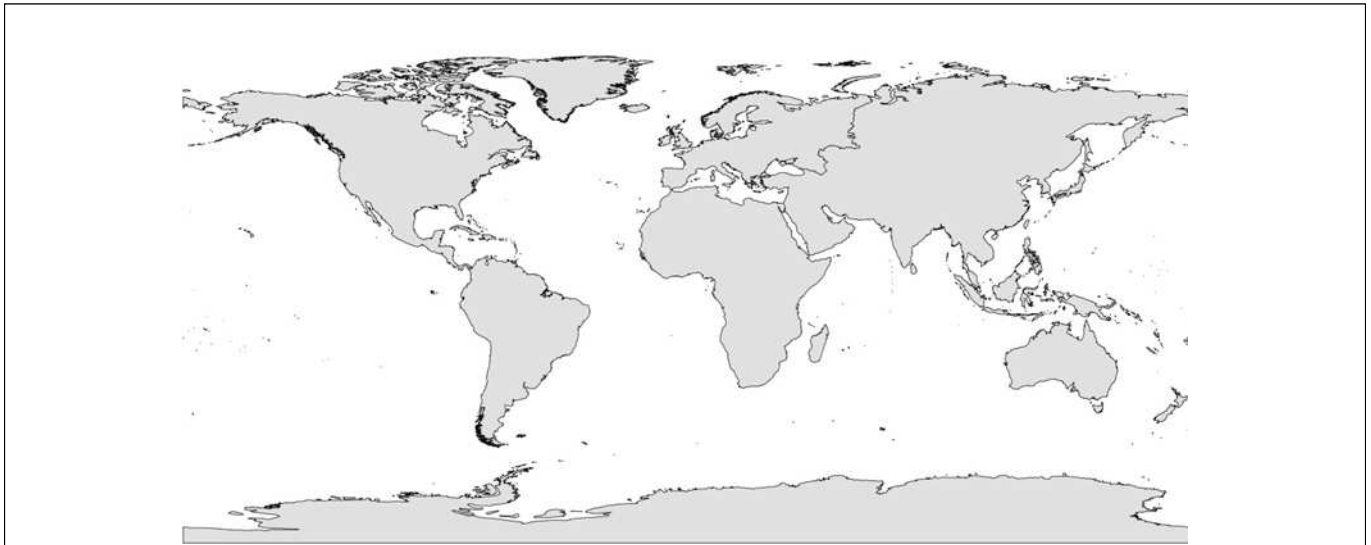


Fig. 8. A map of the world shown in the WGS 84 geographic coordinate system.

to, that coordinate system. Basic knowledge about coordinate systems is recommended before any type of spatial analysis is conducted as they can affect the resulting outputs. It is also important to know the capabilities and weaknesses of each specific coordinate system used in analysis. For more in-depth information about coordinate systems in GIS see Seeger (1999).

4.1. Geographic coordinate systems

A geographic coordinate system is defined by the ellipsoid and datum that are used to calculate longitudes and latitudes which represent locations on the Earth's surface (Snyder, 1987). It is represented in degrees, minutes, and seconds north or south of the equator (latitude) or east and west of the equator (longitude) (i.e. Fribourg, Switzerland is at 46° 48' 00" N, 7° 09' 00" E), and is the simplest solution for representing places on the globe (Burrough and McDonnell, 1998). Decimal degrees are also used to represent latitude/longitude coordinates and can be calculated with the following equation: $\text{Decimal Degrees} = \text{Degrees} + \text{Minutes}/60 + \text{Seconds}/3,600$ (<http://support.esri.com/en/knowledgebase/techarticles/detail/27215>) (i.e. same location above would be represented as 46.8 N, 7.15 E). There are various online sources for calculating conversions between latitude/longitude and decimal degrees (e.g. <http://transition.fcc.gov/mb/audio/bickel/DDDMSS-decimal.html>). The most commonly used geographic coordinate system is the World Geodetic System (WGS) 1984 (Fig. 8). However, geographic coordinate systems do not transfer nicely into two dimensions, causing major distortions in distance, area, shape, or direction (Snyder 1987; Seeger, 1999) on a map or computer screen. To solve these issues, projected coordinate systems are used.

4.2. Projected coordinate systems

Projected coordinate systems are created to allow a two-dimensional representation on a screen or map sheet (Snyder, 1987). Latitudes

and longitudes are converted to meters with respect to the centre of projection by applying calculations to geographic coordinate systems to counteract and offset the distortions on the map. Map projections have been developed for both local and regional scales. There is a large body of research based on the calculations of map projections (see Snyder, 1987 or Seeger, 1999 for more information). One of the most important things to remember is that all map projections create distortion of a least one parameter of the following: distance, direction, scale, conformity (shape), and area (Snyder, 1987; Seeger, 1999). The goal of map projections is to show specific areas with the least amount of distortion. For specific regions, take Switzerland as an example, a map projection has been created (CH 1903 LV03 - the coordinates for Fribourg in the CH1903 LV03 projection are 577965.97 m E, 183244.73 m N) to display the least amount of distortion for the country, but very high levels of distortion elsewhere (Fig. 9).

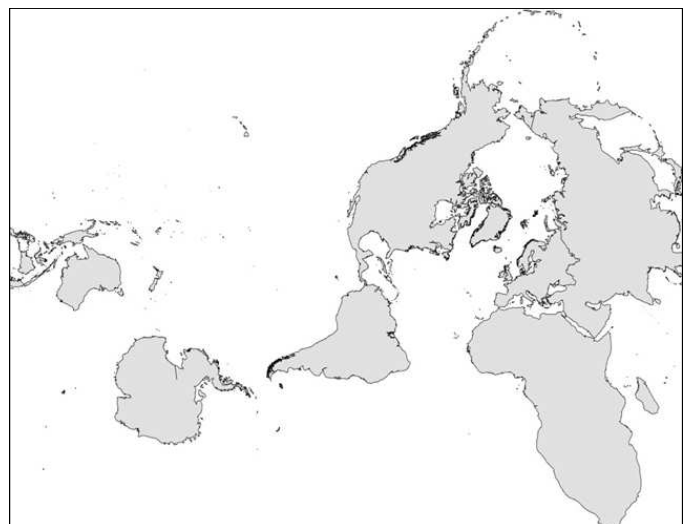


Fig. 9. A map of the world shown in the CH 1903 projected coordinate system.

5. Types of GIS software

Various types of GIS software exist, each with their own strengths and weaknesses. For the purpose of this paper, we will focus on and discuss one commercial off-the-shelf GIS (COTS GIS) software, ArcGIS, and one Free and Open Source GIS (FOSS GIS) software, QGIS.

These two software suites were chosen due to their popularity and use in the field of GIS. Throughout the next sections, some basic functions of GIS will be introduced and explained.

5.1. COTS GIS - ArcGIS

One of the most well-established and popular GIS programs is ESRI's ArcGIS suite. ArcGIS was established in 1969 originally as a research group focused on landuse planning initiatives (ESRI, 2013). Since then, ArcGIS has grown exponentially and is now the leading commercial GIS software which incorporates mobile, desktop, server, and online platforms. Until recently, the licence levels in ArcGIS were organized by the naming scheme ArcView, ArcEditor, and ArcInfo, which denoted the amount of access to tools and functionalities within the software. Now, the different levels are called Basic, Standard, and Advanced, respectively, to make the licence levels more intuitive. The Basic level allows access to mapping and interactive visualization functionalities, the Standard level offers those as well as multiuser editing and advanced data management, and the Advanced level offers all of the above, plus, advanced analysis, high-end cartography, and extensive database management possibilities (ESRI, 2013). These different levels allow the buyer to choose the package that fits their needs. Also, you can add extensions such as Spatial Analyst, 3D Analyst, and Geostatistical Analyst, which are sets of tools for specific tasks (ESRI, 2013). Extensions allow the user to add more advanced functions without the need for upgrading to a different licence.

However, one major problem with ArcGIS and other ESRI products are costs, which can often only be afforded by large corporations, universities, and government agencies. Students or research groups can often acquire versions for free, or at reduced costs, respectively. However, the price is often a deterrent when a company or individual is choosing which GIS software to purchase. Free trials are also available from <http://www.ESRI.com/software/arcgis/arcgis-for-desktop/free-trial>. Also, various online training courses (<http://training.esri.com/>), tutorials (<http://resources.arcgis.com/en/help/main/10.1/index.html#//00qn0000013t000000>), and other resources (<http://resources.arcgis.com/en/home/>) are available online to help with specific tasks.

5.2. FOSS GIS - QGIS

Open Source software is gaining ground in the GIS software business. The scientific community is coming together to use, create, and enhance open source GIS tools. The development of open source GIS is usually driven by very active communities closely collaborating with

different university-level institutions and thus oriented to concrete solutions, e.g. in environmental science or modelling and on technological improvements. Besides that, most open source software is available for free and the users can benefit from the availability and transparency of the open source (program) code, which may be adapted for specific consumer needs and can again be shared within the community. Furthermore, open source software becomes more and more platform-independent and integrative between various projects, libraries, and standards. Some of the software that exists for open source GIS includes the System for Automated Geoscientific Analysis (SAGA, <http://www.saga-gis.org>), the Geographic Resources Analysis Support System (GRASS, <http://grass.osgeo.org>), and Quantum GIS (QGIS, <http://www.qgis.org/>). QGIS is based on an intuitive mapping interface with optional plugins (supplementary program code providing additional functionalities, similar to ESRI ArcGIS extensions) for geoprocessing, analysis, and interoperability with various other software, standards, and data types. GRASS is more advanced in terms of its inherent spatial analytical ability especially for raster data, but some programming knowledge is of advantage for more sophisticated analysis and script automation. The integration of GRASS applications in QGIS through a plugin has a long tradition in the QGIS history, meaning that one can benefit from the strengths of both systems at once. Furthermore, the latest releases of QGIS provide a toolbox called "SEXTANTE" (<http://www.sextantegis.com>) where various Open Source software and libraries like SAGA can be accessed through the straightforward user interface of QGIS. Chapter 7 provides a tutorial for QGIS with basic applications adapted to honey bee research. For further information about open source GIS software and the different projects mentioned above see the Open Source Geospatial Foundation website <http://www.osgeo.org>.

5.3. Tutorial data

The following sections contain step by step information on how to complete certain GIS tasks using both ArcGIS and QGIS. To follow these steps, the file "GISBEEBOOK", can be downloaded from (<http://www.ibra.org.uk/articles/GISBEEBOOK>). Download the data and save them in a location with a few gigabytes of space available. Within the GISBEEBOOK folder, there are two sub-folders, one for ArcGIS and one for QGIS, each containing the same original data. When working through each tutorial, it is recommended that you save your outputs in the respective software's folder to help with file and data organisation. Both folders are located within the GISBEEBOOK folder. The GISBEEBOOK file contains the two folders (ArcGIS and QGIS) with the following data layers in each:

- Point file: This file was created solely for the purpose of this exercise and does not represent the actual locations of honey bee colonies.
- ◊ ArcGIS: An Excel file containing point locations: *colony_locations.xlsx*.

- ◇ QGIS: A comma-separated text file (*.csv) containing the same point locations: *points-table.csv*.
- A shapefile containing commune information: *commune_boundary_FR.shp* (plus 6 other file extensions which must stay together). This data comes from a clip of the Vector200 Swisstopo (Swisstopo, 2013) data layer which is provided to the readers of this paper for testing purposes only and cannot be shared or used for data analysis purposes outside of this tutorial. Communes are a type of administrative unit in Switzerland.
- 30 m DEM:
 - ◇ ArcGIS: Located within the DEM folder: *aster30_frib_ch.tif* (along with 4 other extensions that should be kept together with this file for georeferencing purposes). This DEM was a free download from the ASTER GDEM website (<http://gdem.ersdac.jspacesystems.or.jp/>). The projection was previously changed to the Swiss coordinate system (CH1903) and clipped to the area around Fribourg.
 - ◇ QGIS: ASTER30_WGS84.tif. Also downloaded from the ASTER GDEM website but left in the WGS 1984 coordinate system.

6. Using ArcGIS (version 10.1)

6.1. Main components of ArcGIS

The main components of ArcGIS include ArcMap, ArcCatalog, and ArcToolbox, however, the other platforms that are included in ArcGIS for Desktop are ArcScene and ArcGlobe which both enable 3D data viewing and manipulation. ArcGIS has also grown to include mobile applications, map viewers (ArcGIS Explorer: <http://www.esri.com/software/arcgis/explorer>), and cloud mapping (www.arcgis.com), which will be discussed in section 6.10.10. For more information about ArcGIS in general refer to Ormsby *et al.*, 2010.


6.1.1. ArcMap

ArcMap (Fig. S 10) is the main interface for conducting analyses and creating maps. Here, feature classes and shapefiles can be populated, data can be edited, calculations can be performed, and finally, maps can be created for displaying the results of the GIS analysis. ArcMap projects are stored as map documents (*.mxd) which save all of the layers added to the map as well as the results of any of the geoprocessing tools which were used. It is important to note that the *.mxd does not store the actual data, but only references to them and user-defined layer organization and symbols. Upon first opening ArcMap (*Start menu > All programs > ArcGIS > ArcMap 10.1*) a dialog box will pop-up. Select a recently used map from the list, browse to a map that was previously saved, or just click *Cancel* or close the window to open a blank map.

6.1.2. ArcCatalog

ArcCatalog (Fig. S 11) is where GIS data can be searched for, previewed, and managed. Also, some ArcToolbox tasks can be performed and visualized, but not overlaid with other layers like in ArcMap. Since ArcGIS version 10.0, a more compact version of ArcCatalog can also be accessed directly in ArcMap. ArcCatalog should be used when geographic data are added, moved, or deleted from GIS in order to avoid losing important file extensions (e.g. the geographic reference, see section 3.1 for more information). To open ArcCatalog: *Start menu > All programs > ArcGIS > ArcCatalog 10.1*.

6.1.3. ArcToolbox

ArcToolbox (Fig. S 12) is where all of the geoprocessing and spatial analysis tools are located. There are hundreds of tools available and they range from basic to advanced. The toolbox can be accessed in both ArcMap and ArcCatalog by clicking the  icon from the standard tools menu or by selecting *Geoprocessing > ArcToolbox* from the main menu. To easily find a tool, type the name of the tool into the *Search* window to save time from manually searching through the toolbox. In the following sections, some of the more basic toolbox tools will be discussed, but this is by no means an exhaustive tutorial.


6.2. Navigating the software

At first, the multiple functionalities and options within ArcGIS may seem overwhelming, but there are a lot of resources that exist to help navigate the software and search for help if there are problems.

6.2.1. Help menus

Help menus can be accessed by choosing *Help* from the main menu, or by pressing *F1*, in both ArcMap and ArcCatalog. The entire ArcGIS help menu can also be found online, which is slightly more intuitive and easier to search through. The online help menu can be found at: <http://resources.arcgis.com/en/help/main/10.1/>. For previous versions of ArcGIS, the help menus can be found at <http://resources.arcgis.com/en/help/previous-help/index.html>.

6.2.2. Search window

The *Search window* can be found in the standard toolbar () or by selecting *Customize > Search* from the main menu. The search window can be used to search for GIS content including data located on the computer and tools within ArcGIS.

6.2.3. Toolbars

In ArcMap there are a variety of toolbars, used for different tasks, to choose from. To display or hide toolbars, from the main menu select *Customize > Toolbars* and check which ones to display and hide. By hovering over the tools in the toolbars you can see the name of each respective tool.

6.2.4. General reminders, shortcuts, timesavers

Here is a list of items that will save time when using ArcGIS:

- Naming schemes for files, folders, and anything else associated with ArcGIS should not have spaces. Instead, underscores (“_”) should be used when a space is needed.
- In case data or project files (*.mxd) are moved to a different location, it is useful to save the relative paths of the data so that ArcMap is able to automatically locate the data without having to manually point to the data every time in ArcMap (when ArcMap cannot find the data, a small red exclamation (!) point appears beside the layer in the table of contents (TOC)). To do this:
 - ◊ *File > Map Document Properties > Pathnames: check the “Store relative pathnames...” option.*
 - ◊ To make this feature permanent, go into the ArcMap options *Customize > ArcMap Options > General tab > and check the “Make relative paths the default for new map documents”.*
- Also while in the ArcMap options, have a look at the other options and customize your ArcMap interface to fit your needs.
- When both ArcCatalog and ArcMap are open on the desktop, files from ArcCatalog can be directly dragged and dropped into ArcMap without having to use the *Add Data* button.
- After performing geoprocessing or spatial analyses, the results for all tasks are stored in the results window which can be opened by selecting *Geoprocessing > Results* from the main menu in ArcMap. The *Results* window is useful for keeping track of the tools you already used and easily allows you to reuse them again with alterations to the inputs.
- The naming of raster layers in grid format (ArcGIS native format) cannot be more than 13 characters long.
- Save frequently to avoid losing work!

6.3. Setting the coordinate system and adding data to ArcMap

Upon opening ArcMap, first close the pop-up to open a blank map. It is good practice to set the coordinate system to match the data which will be added, but this step is not required as ArcMap will take on the same coordinate system as the first layer that is added. All subsequent data will be projected “on-the-fly” to the coordinate system specified in the first layer. This will become more apparent later.

6.3.1. Setting a coordinate system and saving a new map document (*.mxd)

Setting the correct map units is important for all types of quantitative analysis and for appropriate cartography. Despite on-the-fly projection capabilities, if layers are in different coordinate systems, this will pose major problems in the display and analysis of data.


To set the coordinate system of the map document:

1. Go to *View*.
2. Select *Data Frame Properties*.
3. Open the *Coordinate System* tab.
4. For the remainder of this paper, we will use data from Switzerland, therefore we will use the projected coordinate system called CH1903 LV03. Double-click *Projected Coordinate Systems*.
5. Double-click *National Grids*.
6. Double-click *Europe*.
7. Select the *CH1903 LV03* option.
8. Click *OK*.


Or:

1. Using the search bar, directly type in the following: CH1903 LV03.
2. Click the *Search* button.
3. Double-click on *Projected coordinates folder > select the CH1903 LV03* option from the list
4. Click *OK*.
5. To save these properties in the map document (*.mxd), go to *File*.
6. Click *Save As*.
7. Name the file and click *OK*.

6.3.2. Add data button

Data can be added from *File > Add Data > Add Data* or by selecting the Add Data symbol  from the standard toolbar. Alternatively, data can be added via drag and drop from ArcCatalog. Since version 10.0, there are also the options of adding base map and other data from ArcGIS online. This will be discussed further in the cloud mapping section (6.10.10.).

6.3.2.1. Connecting to folders




To access the tutorial data, first the GISBEEBOOK folder must be connected to. Browse to the location of the GISBEEBOOK folder using this icon  in the Add Data dialog box. This path to the GISBEEBOOK folder is now saved for the next time data are added from the same folder.

6.3.3. Importing vector and raster data

Vector data are point, line, and polygon features on the map which represent real world entities while raster data represent continuous features such as altitude or satellite imagery (see section 3.2. for data explanations). Here we will add a polygon layer which represents the administrative boundaries in and around Fribourg, Switzerland, and a DEM from the same area.

To add a vector layer:

1. Click the *Add Data* button.
2. Browse to the *commune_boundary_FR* shapefile.

Depending on the type of vector added, it will have a point , line , or polygon  icon. This one is a polygon layer.


3. Single-click the `commune_boundary_FR` shapefile.
4. Click *Add*.

Now the vector layer can be seen in the TOC and in the map.

5. Change the symbology to make the polygons hollow (no fill, thicker line) so the DEM is visible (Fig. S 13).
6. In the TOC the name of any layer can be changed by slowly double-clicking the layer name or by going into the *Properties* > *General* and change the layer name there to make it more intuitive, if needed.
7. Now would also be a good time to save the map document (*.mxd). Go to *File* > *Save* (or use the shortcut Ctrl + s).

To add a raster layer:

1. Click the *Add Data* button.
2. Open the DEM sub-folder in the GISBEEBOOK folder.
3. Double-click the `aster30_frib_ch.tif` file to add it to the map.

In ArcGIS rasters are represented by this icon . Now the DEM can be seen in the TOC and on the map (Fig. S 14).

6.3.3.1. Importing XY data from text files

Many people work with spatially related data even without recognizing it, for example when dealing with observation or address data from multiple locations. It is easy to make use of spatial information also from data stored in text files, calculation spreadsheets or any database. Often, point data representing X, Y, and sometimes Z (altitude) coordinates in the real world are contained within text files and can be imported into ArcMap as an Excel spreadsheet (*.xls or *.xlsx), a text file (*.txt), or comma separated value (*.csv) file. To ensure that this is done without problems or annoyances, ensure the data are properly formatted. For example, the field names in the header line of the text file should not use spaces or special characters, nor should the filename.

To add points from a text file (Fig. S 15):

1. Go to *File*.
2. Select *Add Data*.
3. Select *Add XY Data*.
4. Browse to the GISBEEBOOK folder.
5. Double-click the `colony_locations.xlsx` file.
6. Double-click `Sheet1$`.
7. Choose the respective fields that hold the X and Y data (or longitude and latitude, depending on which coordinate system is used). If the file contains altitude information, add that field in the Z field. In this case:
 - a. X Field: POINT_X
 - b. Y Field: POINT_Y

8. The coordinate system has already been defined for this layer.
9. Click *OK*.

It is important to note that this layer is loaded into ArcGIS and available for any display and map creation purpose and also some basic analysis, but not physically stored as geodata in the file system. A warning dialog box (Fig. S 16) may appear which indicates that the created layer will have to be exported to a shapefile if all functionalities are needed.

10. Click *OK*.

Now the points can be seen in the map and the layer can be seen in the TOC.


11. Right-click the "Sheet1\$ Events" layer in the TOC.
12. Select *Data*.
13. Select *Export Data* to export these temporary points and make a permanent shapefile.
14. Choose to use the layer's source data as the correct coordinate system should have already been set in the previous steps.
15. Browse to the GISBEEBOOK/ArcGIS folder to name the files intuitively, for example, we will name this layer `colony_locations`.
16. Save as type: *Shapefile*.
17. Click *OK*.
18. Click *Yes* when asked to display the new layer on the map.
19. Remove the Sheet1\$ Events layer by right-clicking on *Sheet1\$ Events layer*.
20. Select *Remove*. We now have the permanent shapefile, so this temporary layer is no longer needed (Fig. S 17).
21. To change the symbology of the point layer to make the points more visible, either:
 - a. Single-click on the symbol in the TOC and choose the new symbol and size.
 - b. Go into the properties of the layer by right-clicking *Layer*.
 - c. Select *Properties*.
 - d. Click the *Symbology* tab.
 - e. Change the symbol to a yellow circle for example.
 - f. Click *OK*.

Also to note, there are multiple symbol libraries that can be added by clicking the *Style References* button when in the *Symbol Selector* dialog box. The symbol libraries provide more options for symbol styles.

6.3.3.2. Importing GPS data (*.gpx files)

Geographic coordinates, often collected via a handheld Global Positioning Systems (GPS) receiver can be imported and displayed in ArcGIS (since version 10.1). GPS data are in the GPS eXchange Format (*.gpx) and can be converted to shapefiles using the *GPX To Features (Conversion)* tool, which can be found in the *Conversion Tools* toolbox > *From GPS* toolset.

6.3.4. Layer organisation and navigation

It is essential to have some basic knowledge about layer organisation and navigation in order to optimize the map display (e.g. to change the order and how layers are drawn in the *Data View*) and to preserve a good organisation among all the different data, intermediate calculation results and map elements, especially for a growing GIS project with many layers. In ArcMap, the layers will be displayed on the map in the same order as in the TOC. In Fig. S 13 for example, the colony_locations layer is above commune_boundary_FR and aster30_frib_ch.tif layers therefore everything can be seen clearly, since we made the commune boundaries hollow. If the DEM was at the top of the layer list in the TOC then the other two layers would be hidden. At the top of the TOC there are five icons  which allow different views of the data in the TOC. To rearrange the layers in the TOC, select the first icon (*List by Drawing Order*) and click and drag the layers to their new positions. The layers can be turned on and off by checking or unchecking the box beside the layer.


6.3.5. Layer properties

The properties of one specific layer can be accessed by right-clicking the layer and selecting *Properties* from the context menu, or simply by double-clicking the layer name. The *Layer Properties* might vary between different file formats, but every layer will at least have tabs for *Symbology* options, *General* settings and provide metadata (see section 3.) in the *Source* tab. Look at the metadata of the layer commune_boundary_FR.shp by opening the *Source* tab in the *Layer Properties*. Apart from the extent (maximum and minimum values for X and Y), data source, and geometry type, there is also information about the coordinate system and projection used. From the *Display* tab, the transparency of the layer can be set and the *Labels* tab enables the labelling of features in the layer.

6.4. Database investigations and editing

Some databases have hundreds, if not thousands or millions, of entries. This makes manual searching almost impossible. Like any other form of database management system, ArcMap offers a number of options to efficiently browse, select, export and edit these records.


6.4.1. Queries

One of the characteristics of GIS is the possibility to combine information about several layers and datasets by using a geographic reference, e.g. a given point, a set of polygons or specific grid cells in a raster image. Queries are used to locate specific records from tables or places on the map based on the shared properties of layers. In GIS, a query can refer to two different functions. The first is a very basic GIS function that enables the user to interactively obtain information about a specific location in the GIS, using the *Identify*  tool. The *Identify* tool is used to get information about specific pixel values within a raster image or to look at the attribute values of vector

feature. In the example (Fig. S 18), it can be seen that the location on the map which was clicked is somewhere in the commune of Düdingen and has an altitude of about 612 m. This information comes from the commune layer and the DEM that are currently in the ArcMap *.mxd.

The second, more advanced, type of query in GIS refers to the database query. This type of query uses a structured query language (SQL), adopted from database management systems, which allows the retrieval of information from the database (Longley *et al.*, 1999). In ArcMap, the tool that incorporates SQL is the *Select by Attributes* (6.4.1.1.) tool. To go beyond the database search, the *Select by Location* (6.4.1.2.) tool can be used for geographic or locational queries of data. Selections can also be conducted manually using the *Select Features* tool (6.4.1.3.). These three selection methods can also be used in combination by changing the method of selection (*Create new selection*, *Add to current selection*, *Remove from current selection*, *Select from current selection*) in each respective dialog box. Any selection can be removed by clicking the *Clear Selected Features* button.



6.4.1.1. Select by attributes

The *Select by Attributes* tool is located on the main menu in *Selection > Select by Attributes*, or also within the attribute table of each layer: *Right-click layer > Open Attribute Table > Table Options*  > *Select by Attributes*. This tool allows the user to select a set of data from a layer based on the attribute properties of the layer. In the following example, all the communes within the canton of Fribourg, Switzerland, will be selected because all of the honey bee colonies are within that canton.

1. From the main menu, go to *Selection*.
2. Click *Select by Attributes*.
3. The input layer is the layer from which data will be selected. In this case, choose the commune_boundary_FR layer as input.
4. There are multiple methods available:
 - a. *Create new selection*,
 - b. *Add to current selection*,
 - c. *Remove from current selection*,
 - d. *Select from current selection*.
5. Choose *Create new selection*.

In the next section there is a list of attributes corresponding to those of the input layer.

6. Select the *KANTONSNR* attribute by double-clicking on the name.
7. Click the equals = button.
8. Click the *Get Unique Values* button to see all the values in that attribute field. In this case, the values represent two cantons in Switzerland.
9. Double-click the *10* to add it to the equation. In this example, 10 was clicked because that is the canton number for Fribourg.
10. Now the SQL equation looks like this: `SELECT * FROM commune_boundary_FR WHERE: "KANTONSNR" = 10` (Fig. S 19).


11. Click *OK*
12. Open the attribute table of the layer from which data were selected (*Right-click > Open attribute table*).
13. Click the *Show selected records* button to view the records corresponding to the selection .
14. The selected records (49 out of 51) in the table match those selected on the map (Fig. S 20).
15. Now the selection can be cleared using the icon  to begin a new selection in the next section.

6.4.1.2. Select by location

Now two layers will be used to select the communes which have colonies inside them. To do this (Fig. S 21):

1. Go to *Selection*.
2. Choose *Select by Location*.
3. Choose the Selection method: select features from the target layer: *commune_boundary_FR*.
4. Select the Source layer: *colony_locations*.
5. Select the Spatial selection method: intersect the source layer feature (this tool has various options for spatially querying data and applying search distances to discover geographic relationships).
6. The selected results: 11 records out of 51 (Fig. S 22), meaning 11 communes had colonies inside their boundaries.

6.4.1.3. Manual selection

Data can also be selected manually with the *Select Features* tool  in the *Tools* toolbar. With this tool, you can select the data by various shapes (rectangle, polygon, circle, etc.) and export the selected items to their own shapefile (see section 6.4.2.).

6.4.2. Creating new layers from selected data

If a selection of data has to be exported, to send to someone who needs only a part of a data layer, for instance, a new data layer can be created with the selected features. We will create a new layer with the data selected in section 6.4.1.2.

1. Perform step 6.4.1.2.
2. Close the *Select by Location* dialog box.
3. Right-click on the *commune_boundary_FR* layer in the TOC.
4. Go to *Data*.
5. Select *Export Data*.
6. Select Export: *Selected features*.
7. Use the same coordinate system as the source data.
8. Save as a new shapefile in the ArcGIS BEEBOOK folder. Call it *colony_communes.shp*.
9. Click *Save*.
10. Click *OK*.
11. Click Yes to add the new layer to the map.
12. Clear the selected features, go to *Selection*.
13. Click *Clear selected features*.

14. Turn off the *commune_boundary_FR* and *aster30_frib_ch.tif* (DEM) layers in the TOC.
15. Right-click on the *colony_communes* layer.
16. Click *Zoom to layer* (Fig. S 23) to focus the map on that layer.

6.4.3. Attribute table data editing

Not only can the attributes of layers be displayed and used for selection, but they may also be changed or removed. The data in tables can be edited and new fields can be added and populated. The attribute table for the *colony_locations* layer has two fields with no data in them. To populate information about the site location and the apiary number (as examples), the table can be edited.

To edit attribute tables:

1. Right-click the *colony_locations* shapefile.
2. Go to *Open Attribute Table*.
3. Open the *Editor* toolbar.
4. Go to *Customize*.
5. Select *Toolbars*.
6. Select *Editor*.
7. From the *Editor* toolbar, select *Editor*.
8. Select *Start Editing*.
9. Choose the *colony_locations* layer to be edited.
10. Click *OK*.

Previously the column names in the attribute table were grey; when in editing mode they will turn white which means they are editable (Fig. S 24).

11. Click in the cell to edit and type the information. Information can be manually typed or if the information exists in a text file, copy and paste them into the table while in editing mode.
12. Periodically save your edits: Click *Editor*.
13. Click *Save Edits*.
14. Click *Editor* again.
15. Click *Stop Editing* to end the editing session.

6.4.4. Add new field

To add a new field to the table:


1. Open the table options .
2. Select *Add field*. Note: Fields can only be added outside of the editing mode!!
3. Name the new field you would like to add.
4. Select the type of data which will populate it (see Table 3 to learn about data types).
5. Click *OK*.
6. A message might warn you that you are performing calculations outside of an editing session. Check the *Don't warn me again* option.
7. Click *Yes*.
8. To manually add information to the new attribute field, go into the editing mode and type them into the new field.

Table 3. Description of data types which are found in attribute tables, as well as the range of numbers or text they store and their uses.

Adapted from the ArcGIS help menu (ESRI, 2013).


Data type	Storable range	Applications
Short integer	-32,768 to 32,767	Numeric values without fractional values within specific range; coded values
Long integer	-2,147,483,648 to 2,147,483,647	Numeric values without fractional values within specific range
Single-precision floating-point number (float)	approximately -3.4E38 to 1.2E38	Numeric values with fractional values within specific range
Double-precision floating-point number (double)	approximately -2.2E308 to 1.8E308	Numeric values with fractional values within specific range
Text	---	Store alphanumeric symbols
Date	---	Store dates, times, or both

6.4.4.1. Advanced table calculations

1. For more advanced table management:
 - a. Use the field calculator to calculate the inputs in the field:
 - i. Right-click new field name.
 - ii. Select *Field Calculator*.
 - iii. Use computer programming code to write the equation for the calculation.
 - b. Use the calculate geometry option to calculate the x and y coordinates of point layers, or areas, and centroids of polygon layers:
 - i. Right-click on *New Field Name*.
 - ii. Select *Calculate Geometry*.
 - iii. Choose one of the calculation options.

a bigger layer. Note: A specific example is not shown here, but this is how the tool would be used.

To use the Clip tool:

1. Open the *Search* window .
2. Type "clip" (or browse to *Analysis Tools > Extract > Clip* in the ArcToolbox).
3. Choose the *Clip (Analysis)* tool. This one is for vector data.
4. The Input features layer is the layer that will be clipped.
5. The Clip Feature will be the new extent of the clipped layer.
6. Name and save the new clipped layer.
7. Click *OK*.

6.5. Basic vector tools


The following section shows how to perform selected vector data calculations. The name of the tool will be given and the name of the toolbox in which the tool is located in ArcToolbox will be given in brackets (tool (toolbox)).

6.5.1. Clip

Using the *Clip tool*, two layers can be overlaid with each other. The output layer (which has to be specified as a new vector file) will contain the content of the first layer (Input vector layer) reduced to the geometry and extent of the second layer (Clip feature) (Fig. 25). A similar process is also followed when clipping raster data, but the *Clip (Data Management)* tool is used instead. This tool is also useful if you require all data layers to have the same spatial extent, for example if you are working with a specific region and only need a small piece of

6.5.2. Intersect

The *Intersect (Analysis)* tool computes a geometric intersection of the layers. Only those input features which overlap will be included in the output layer. This tool is useful for connecting multiple layers and joining their attributes together, by discarding the portions which do not overlap. In the next example, we will intersect the colony_locations layer (colony locations) with the colony_commune layer so that the intersected layer will have the point locations but also the commune information for each point. To use the intersect tool (Fig. S 26):

1. Open the *Search* window .
2. Type "intersect" (or browse to *Analysis Tools > Overlay > Intersect* in the ArcToolbox).
3. Choose the *Intersect (Analysis)* tool.
4. The Input Features will be all of those to intersect, in this case the colony_locations and colony_communes layers.
5. Save the output as intersect.shp.
6. Leave the defaults for the rest of the options.
7. Click *OK*.

In this case, the resulting geometry of the point file has not changed, but the attribute table of the intersected layer now includes the colony locations and commune information (Fig. S 27).

6.5.3. Union

The *Union (Analysis)* tool is used to create a geometric connection between polygon layers where all features and geometries will be added to the resulting layer. The union function is useful when the

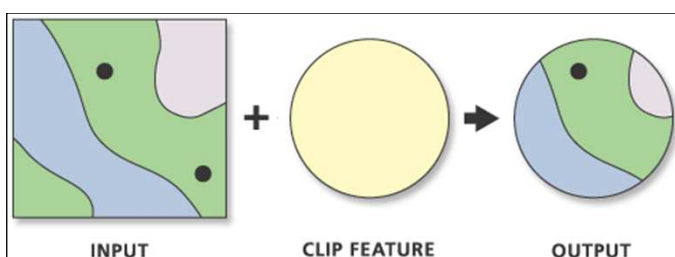


Fig. 25. A visualisation of how the clip tool works in ArcGIS taken from the help menu (ESRI, 2013).

geometries and attributes of different layers should be merged. In ArcGIS, all input polygons will be transferred to the output layer, regardless as to whether they spatially overlap or not, leaving the resulting dataset with three feature types: those found only in the first input layer, those found only in the second input layer, and those found in both the first and second input layers (Ormsby *et al.*, 2010).

6.5.4. Spatial join

In section 6.4.1. spatial queries were performed. In a similar manner, multiple layers can be spatially linked to each other using the *Spatial Join (Analysis)* tool. Spatial joins allow the attributes of features in separate layers to be linked together based on their shared spatial locations. This is useful for amalgamating different types of information into the same layer. The *Spatial join (Analysis)* tool can be used to perform this task. The *Target Features* can be any spatial data source supported by ArcGIS and will be transferred to the *Output Feature Class* along with the *Join Features*. The *Join Operation* determines how joins between target and join featured will be handled if multiple join features have the same spatial relationship with a single target feature; one-to-one or one-to-many (search spatial join in the ArcGIS online help menu for more information).

6.5.5. Buffer(s)

Buffers are one of the most important geoprocessing operations and frequently used for data analysis and cartography. A buffer increases the features area by a given radius, exactly following its original geometry (point, line or polygon). Buffers are also useful for determining proximities. For honey bees, this tool could be useful for determining the extent of the foraging radius with regards to various land covers, for example.

6.5.5.1. Single buffer

To create a single buffer (Fig. S 28):

1. Type "buffer" into the *Search* window (or browse to *Analysis Tools > Proximity > Buffer* in the ArcToolbox).
2. Select the *Buffer (Analysis)* tool.
3. Input features will be the colony locations: colony_locations.
4. Create a new output feature class: buffers.shp.
5. Choose "2000 m" as the search radius.
6. Leave the default options for the remaining.
7. Click *OK*.

The results show the buffered area surrounding each point (Fig. S 29).

6.5.5.2. Multiple ring buffers

To create multiple ring buffers (Fig. S 30):

1. Type "buffer" into the *Search* window (or browse to *Analysis Tools > Proximity > Multiple Ring Buffer* in the ArcToolbox).
2. Select the *Multiple Ring Buffer (Analysis)* tool.

3. Input features will be the colony locations: colony_locations.
4. Create a new output feature class: multi_buffers.shp.
5. Type "100".
6. Click the plus sign (+).
7. Do the same for 200, 300, 400, 500, and 1000 m.
8. Choose the buffer unit (meters in this case).
9. Keep the field name of "distance" for the new attribute table of the multiple buffer layer.
10. Keep the default for the dissolve option, otherwise all buffers will be aggregated to one single feature without the different attributes (see section 6.5.7. for more information about Dissolve).
11. Click *OK*.

The results show the multiple buffers created surrounding the points (Fig. S 31).

6.5.6. Summary statistics

A *Summary Statistics (Analysis)* tool exists in ArcGIS and is useful for performing basic calculations on fields in an attribute table. This can be valuable for summarizing large quantities of data within GIS (similar to basic statistics that can be calculated in Excel). For example, the sum, mean, min, max, range, standard deviation, and count can be calculated for each selected attribute. The results are saved in an output table and can be viewed directly in ArcMap. Also, to access the statistics of single fields in an attribute table, *Right-click* the layer in the TOC > *Open attribute table* and then *Right-click field name* and choose the *Statistics* option.

6.5.7. Dissolve

Dissolve is another very useful function that merges several features together, based on their attributes. All features within a given vector layer containing the same attribute value will be combined to one single feature (one entry in the *Attribute table*). Shared borders between these geometries will disappear and in the case of spatially divided (geometrically non-adjacent) input features, the result will be a so-called "multipart" feature. The Dissolve (Data Management) tool is useful for portraying or visualizing specific information from a shapefile. For example, here we used the commune_boundary layer for Switzerland (basically the same as the commune_boundary_FR layer, but for all of Switzerland). The geometry of the layer currently represents the communes of Switzerland, but we want to visualize countries instead of communes. In the attribute table, there is a column indicating which country each commune belongs to, thus we can "dissolve" the administrative boundaries based on that field. In the next example, the attributes in the commune layer will be dissolved to create a new layer based on the country geometry. NOTE: Here we will use a layer that has not been provided in the tutorial. This is to illustrate what might be done using the dissolve tool.

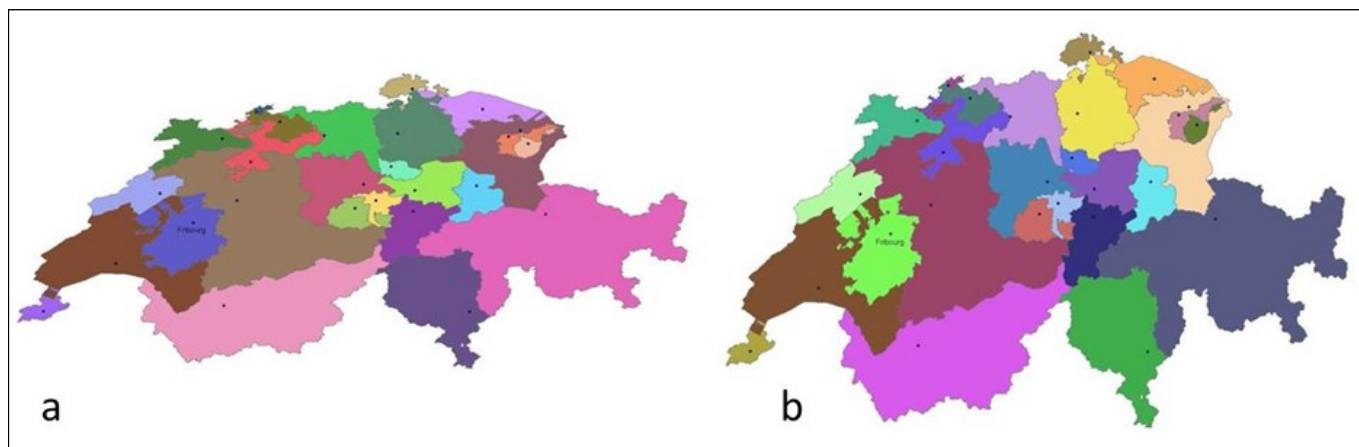


Fig. 36. World Geodetic System (WGS 84, a) versus the Swiss projection (CH1903 LV03, b). Reproduced with permission of Swisstopo (BA13016).

To use the dissolve tool (Fig. S 32):

1. Type "dissolve" into the *Search* window (or browse to *Data Management Tools > Generalization > Dissolve* in the ArcToolbox).
2. Select the *Dissolve (Data Management)* tool.
3. The Input features will be the *commune_boundary* (for all of Switzerland) in this case.
4. Name and save the output layer as a shapefile.
5. In this case we will dissolve based on the *COUNTRY* attribute.
6. Leave the default options for the remaining.
7. Click *OK*.

The result (Fig. S 33) shows that the geometry and the attributes represent only the countries.

6.5.8. Project

Data layers often need to be "projected" to get them into the same coordinate system as other layers. For example, if data comes from different places (e.g. online, governmental agencies) or represents different areas on the map, there is a good chance that the coordinate systems between layers will differ, therefore a projection of the data is required. If layers are not in the same coordinate system and not overlapping correctly, there will be errors in the resulting layers created after analyses. The Project (Data Management) tool is used to change a vector layer from one coordinate system to another. The same process can also be used for raster layers, but the Project Raster (Data Management) tool is used instead. If the layer's coordinate system is unknown, it must first be defined, either in the layer properties in ArcCatalog or by using the Define Projection (Data Management) tool in ArcMap. In this example, we will project the *colony_communes* layer from the Swiss projection to WGS 1984 and import the results into Google Earth (KML file) (6.5.9.).

To use the project tool (Fig. S 34):

1. Type "project" in the Search window (or browse to *Data Management Tools > Projections and Transformations > Feature > Project* in the ArcToolbox).

2. Select the *Project (Data Management)* tool.
3. Input layer: *colony_communes*.
4. The coordinate system of the layer will automatically be added.
5. Save the output as: *commune_wgs84.shp*.
Indicating the new coordinate system in the name is useful for layer organisation.
6. Choose the output coordinate system.
7. Click the *Browse* button.
8. Expand the Geographic coordinate systems option.
9. Click *World*.
10. Select the WGS 1984 coordinate system.
11. Select a transformation from the predefined list. In this case, the first is sufficient.
12. Click *OK*.
13. Click *OK* again.

The resulting layer will possess the new projection and is automatically added to the map document (Fig. S 35). The green *commune_wgs84* polygon layer is slightly shifted to the south compared to the blue *colony_communes* layer underneath. As another example of the differences in coordinate systems, Fig. 36 shows an example from Switzerland between the WGS 1984 coordinate system (a) and the CH1903 projection (b).

6.5.9. Layer to KML and import to Google Earth

A KML (Keyhole Markup Language) file is a geographic data layer which was developed for use with Google Earth. Using these steps, any layer (shapefile or raster) from GIS can be imported to Google Earth (conversely, the *KML to Layer* tool can be used to bring data from Google Earth into ArcGIS). This conversion is useful for sharing geographic information with people who do not use GIS. In previous ArcGIS versions, a shapefile needs to be saved first as a "layer" file before converting it to KML. To do that, the *Save to Layer File* tool can be used. A layer file is basically a pointer to the shapefile which stores specific symbolization properties. In version 10.1, the user is no longer required to save as a layer file before converting to a KML.

To export a layer from ArcMap for import into Google Earth (Fig. S 37):

1. Type "kml" in the *Search* window.
2. Select the *Layer to KML (Conversion)* tool.
3. Input layer: commune_wgs84.
4. Output: GE_commune_wgs84.kmz.
5. Leave the other options with their default values.
6. Click *OK*.
7. Open Google Earth (if not already installed, it can be downloaded from: <http://www.google.com/earth/index.html>)
8. In Google Earth go to *File*.
9. Click *Open*.
10. Select the GE_commune_wgs84.kmz layer.
11. Click *OK*.

The layer created in ArcMap should now be displayed and correctly georeferenced in Google Earth (Fig. S 38).

6.6. Basic raster tools

Some of the previously mentioned vector data tools also exist specifically for rasters, for example, *Clip* and *Project*. However, most raster tools have different names and functionalities which are unrelated to vector analyses. Below, we will briefly touch on some of the basic raster calculations that can be performed, specifically some of the most commonly used tools for terrain analysis and raster file management.

6.6.1. Mosaic

The *Mosaic (Data Management)* tool allows multiple raster layers to be combined with an existing raster dataset, while the *Mosaic to New Raster (Data Management)* tool allows multiple raster layers to be combined together to create a new raster dataset. The input raster images can vary in resolution and extent, but the defined output resolution may cause some input images to increase or decrease in resolution, sometimes leading to a loss in information. Also, the input rasters must have the same predefined coordinate system and the same number of bands.

6.6.2. Surface Analysis

The Surface Toolset in ArcGIS allows you to calculate and visualize different properties of the terrain from an input DEM (see section 3.2.1.4.). The surface toolset is part of the Spatial Analyst toolbox in ArcGIS. In the following section we will perform calculations based on the same 30 m DEM introduced earlier. For the next sections, one of either Spatial or 3D Analyst extensions is required. To turn on extensions select *Customize > Extensions* from the main menu. If you do not own a license, you will get a message when you try to click an extension.

6.6.2.1. Slope

The *Slope (Spatial Analyst or 3D Analyst)* tool calculates the slope of the terrain, either in degrees or percentage rise.

To calculate the slope of the terrain (Fig. S 39):

1. Turn on *Spatial and 3D Analyst extensions*, go to *Customize* (from the main menu).
2. Select *Extensions*.
3. Check the *Spatial Analyst* (and/or *3D Analyst*) extension.
4. Click *Close*.
5. Type "slope" into the *Search* window (or browse to *Spatial Analyst Tools > Surface > Slope* in the ArcToolbox).
6. Select the *Slope (Spatial Analyst or 3D Analyst)* tool.
7. Choose the DEM as the input raster (aster30_frib_ch.tif).
8. Save the output raster as "slope".
9. Choose the output measurement to be used, here we will use degrees.
10. If the X, Y, and Z (altitude) coordinates are all in meters, leave the Z factor as 1. Otherwise click the *Show Help* button in the tool to read about how to convert the Z factor.
11. Click *OK*.
12. Turn off all other layers in the TOC, right-click *Layer* at the top of TOC.
13. Select *Turn all layers off*.
14. Turn on the new slope raster in the TOC.

The results show the default classification scheme in degrees ranging from 0 to about 58 degrees in eight categories (Fig. S 40).

Now the results will be classified in a different way by opening the layer properties (Fig. S 41).

15. Right-click *slope* layer in the TOC.
16. Select *Properties*.
17. Select the *Symbology* tab.
18. Choose the "stretched" option in the Show dialog box.
19. Select a colour ramp.
20. Choose the stretch type of Minimum-Maximum.
21. Click *OK*.

The results (Fig. S 42) show that the region is not so diverse in terms of slope.

6.6.2.2. Aspect

The *Aspect (Spatial Analyst or 3D Analyst)* tool calculates the direction in which slopes are facing. Values are given in degrees in regards to the degrees on a compass (with north as 0 and 360 degrees).

To calculate the aspect of the terrain (Fig. S 43):

1. Type "aspect" into the *Search* window (or browse to *Spatial Analyst Tools > Surface > Aspect* in the ArcToolbox).
2. Select the *Aspect (Spatial Analyst or 3D Analyst)* tool.
3. Choose the DEM as the input raster.
4. Save the output raster as aspect.
5. Click *OK*.

In the TOC the results (Fig. S 44) can be seen in degrees.

6.6.2.3. Hillshade

Shaded relief rasters (also called hillshade) are frequently used for visualization and cartographic purposes and are calculated from a DEM and predefined values for the azimuth (horizontal deviation from north, clockwise) and the solar elevation angle (vertical inclination between the sun and the horizon). The *Hillshade (Spatial Analyst or 3D Analyst)* tool calculates the shaded relief of the terrain in ArcGIS. This tool is useful for determining which areas of the terrain are shaded and which are not, during certain hours of the day, month, or year.

To calculate the hillshade of the terrain (Fig. S 45):

1. Type "hillshade" into the *Search* window (or browse to *Spatial Analyst Tools > Surface > Hillshade* in the ArcToolbox).
2. Select the *Hillshade (Spatial Analyst or 3D Analyst)* tool.
3. Choose the DEM as the input raster.
4. Save the output raster as aspect.
5. Click *OK*.

The results will be shown in a greyscale with values ranging from 0 to 254 (Fig. S 46), where 0 is black, representing completely shaded areas, 254 is white, representing illuminated areas, and all values in between representing an increasingly lighter shade of grey, thus different levels of illumination from the sun.

Hillshade rasters are good for visualizing terrain under different layers. To display the terrain properties under the DEM:

1. Drag the hillshade layer to the bottom of the layer list in the TOC.
2. Turn off all of layers except for the hillshade and the DEM.
3. Open the properties of the DEM, right-click *DEM* layer.
4. Select *Display*.
5. Set the transparency to 50%.
6. Go to the *Symbolology* tab.
7. Select a different colour ramp.
8. Click *OK*.

The resulting image (Fig. S 47) enables a more intuitive view of the terrain with high elevations in red, low elevations in green, and the ability to see shadows from the hillshade.

6.6.2.4. Contour

The *Contour (Spatial or 3D Analyst)* tool generates an output vector file containing elevation levels (contour lines) from an input raster (in most cases a DEM). Contour lines are frequently used in cartography as they can easily be combined with other raster images (like aerial photos or pixel maps).

To generate contour lines from a DEM:

1. Open the *Search* window.
2. Type "contour" (or browse to *Spatial Analyst Tools > Surface > Contour* in the ArcToolbox).
3. Use a DEM as the *Input raster*.

4. Choose a location to save the *Output polyline features* (vector format).
5. Define the *Contour interval* which will be the distance between the contours (if you are using the Swiss projection this will be in meters).
6. Set the optional *Base contour* value, if desired (contours will start after the base value).
7. If using a different unit than meters, click the *Z factor* input box.
 - a. Click *Show Help* to learn about Z factor conversions.
8. Click *OK*.

The new vector line file will be generated and added to the document. To achieve better results for visualisation, a smoothing algorithm could be performed on the line feature, e.g. with the tool *Simplify* or *Smooth Line (Cartography Tools > Generalization > Simplify* or *Smooth Line* from the ArcToolbox).

6.6.3. Zonal statistics

The *Zonal statistics (Spatial Analyst)* tool calculates the statistics on values of a raster within the zones of another dataset. For example, buffers could be used as input zones to calculate the statistics from any raster layer (DEM, slope, aspect, etc.) to determine the mean, majority, maximum, median, minimum, minority, range, standard deviation, sum, or variety of the raster pixels which are located within the buffer confines. The results are contained in a new raster layer and this should be conducted for each statistic required. To obtain multiple statistics at one time, the *Zonal Statistics as Table (Spatial Analyst)* tool can be used to generate the statistical results in table form for either all or selected statistic types. For an example of the use of the zonal tools, see the case study in section 6.9.7.

6.6.4. Raster calculator

The raster calculator is used for more advanced raster calculations, including raster math and building conditional and trigonometric expressions. It can be found using the search window or in the *Spatial Analyst > Map Algebra* toolset. For example, the formula "aster30_frib_ch.tif" * 3.28084" would convert the elevation data in the DEM from meters into feet by creating a new raster image. For more information search "raster calculator" in the help menu (<http://resources.arcgis.com/en/help/main/10.1/>).

6.7. Format conversions

ArcGIS provides a variety of different conversion functions between vector and raster data formats similar to other GIS software. As both of these formats have their advantages and disadvantages (see section 2.2.) in terms of data management, analysis, and display options, format conversions should be clearly linked to a precise purpose (e.g. when an elevation model is only available as raster data, but a map containing contour curves has to be created). There

are various tools available to switch between data formats. See the *Conversion Tools* toolbox to view all of the options. The most common conversions are between raster and vector formats. Conversion operations can lead to data loss or decreased precision – so apply these functions with care.

6.7.1. Vector to raster

This function rasterizes vector geometries (Fig. 2) into the band(s) of a raster image (Fig. 3).

To convert to a raster from a vector:

1. Expand the *Conversion Tools* in the ArcToolbox.
2. Select *To Raster*.
3. Depending on the type of vector data you want to convert, select either *Point to Raster*, *Polygon to Raster*, or *Polyline to Raster*.
4. Indicate where the output will be saved.
5. Click *OK*.

6.7.2. Raster to vector

To convert to a vector from a raster:

1. Expand the *Conversion Tools* in the ArcToolbox.
2. Select *From Raster*.
3. Depending on the type of vector data you want to convert to, select either *Raster to Point*, *Raster to Polygon*, or *Raster to Polyline*.
4. Indicate where the output will be saved.
5. Click *OK*.

6.8. Spatial Statistics

The purpose of this section is to introduce the *Spatial Statistics* toolset in ArcGIS so that researchers are aware of its existence. Since most of the same tools can be found in other statistical packages, they will not be explained here in-depth, but their geographic links will be discussed. For more information on these tools see the overview in the ArcGIS online help menu by typing “An overview of the Spatial Statistics toolbox” into the search window. Additionally, see Lee and Wong (2001) or Wong and Lee (2005) for further tool descriptions. Be aware that these texts used previous versions of ArcGIS so the tutorials are not completely compatible. Unfortunately, these are the most updated versions available.

6.8.1. Analysing patterns

This toolset includes: Average Nearest Neighbour, High/Low Clustering (Getis-Ord General G), Incremental Spatial Autocorrelation, Multi-Distance Spatial Cluster Analysis (Ripley's K Function), and Spatial Autocorrelation (Morans I). These tools can be used for analysing spatial patterns based on features, or the values associated with features.

6.8.2. Mapping clusters

Cluster and Outlier Analysis (Anselin Local Morans I), Grouping Analysis, and Hot Spot Analysis (Getis-Ord G_i^*) are located in this toolbox and can be used to identify statistically significant hot spots, cold spots, and outliers.

6.8.3. Measuring geographic distributions

These tools enable the researcher to ask spatially defined questions about their data by using the Central Feature, Directional Distribution (Standard Deviational Ellipse), Linear Directional Mean, Mean Center, Median Center, and Standard Distance tools.

6.8.4. Modelling spatial relationships

This toolset can be used to conduct regression analyses or creating spatial weights matrices. The tools include Exploratory Regression, Generate Network Spatial Weights, Generate Spatial Weights Matrix, Geographically Weighted Regression, and Ordinary Least Squares.

6.9. Case study – zonal statistics with land cover properties

Until now, several concepts and tools in ArcGIS have been introduced. Now, to combine some of the different tasks discussed, a case study will be presented. Within this short case study, geostatistical relationships between honey bee colonies and land cover properties will be calculated. The content of this case study is equal to the one for QGIS (see section 7.9.), but adapted to the tools of ArcGIS. The prerequisite for this case study is an ArcMap document (see section 6.3.) with a point vector layer (e.g. the honey bee colony locations *colony_locations.shp*, created in section 6.3.3.1.) and a buffer polygon layer (e.g. *buffer.shp*, created in section 6.5.5.1.). In this case study, the percentages of land cover types within 2 km radii of honey bee colony locations will be calculated. This will allow the user to obtain information about forage availability near colony locations. First, you will go through the process of downloading the Corine (which means “coordination of information on the environment”) Land Cover 2006 (CLC06) dataset from an online source. The CLC06 layer is a free 100 m resolution raster representing 50 different land cover classifications for the continent of Europe including, agricultural areas, forests, wetlands, and water bodies (for more information see <http://sia.eionet.europa.eu/CLC2006>). This layer will then be projected to the Swiss coordinate system and clipped to the study region around Fribourg, Switzerland in order to make analysis and map rendering more time efficient. You will then learn how to assign land cover codes and a predefined colour scheme to the CLC06 layer and how to optimise the layer for the study region. After, raster calculator will be used to calculate conditional rasters which will be used as the basis of the statistical analysis for determining land cover types within the 2 km radii surrounding each honey bee colony location.

6.9.1. Downloading data and changing projection

First, land cover data for the region surrounding Fribourg will be downloaded and extracted.

1. *Download* the dataset *g100_06.zip* (CLC06 – 100 m) from the website <http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2> to a local directory (e.g. on the Desktop).
2. *Unzip* the file *g100_06.zip* with a file archiving program of your choice (if you need additional software for this task, the program "7-zip" is a good choice: www.7-zip.org) into your ArcGIS working directory (e.g. the GISBEEBOOK folder). Note: data in zipped folders cannot be seen in ArcGIS applications so you must first unzip.
3. Open ArcCatalog.
4. Navigate to folder containing the land cover raster *g100_06.tif* and select the *Preview* tab to get a visual impression of the data. As you can see, the data layer covers all of Europe.
5. Now open the *Properties* of the raster layer by double-clicking the layer name.

From the *General* tab in the layer properties, you see that CLC06 is a 1 band raster dataset with 8 bit unsigned integer values (that correspond to different land cover categories) at 100 m horizontal resolution. Because it covers all Europe, the CLC06 raster is quite large and the rendering on the screen may take some time. We will improve the performance by clipping to the extent of interest. The coordinate system is different (ETRS89_ETRS_LAEA) than the one used in Switzerland therefore it is best to project it into the same coordinate reference system as the other layers (CH1903 LV03).

6. Now, add the CLC06 layer into a new blank *.mxd by dragging the layer from ArcCatalog into ArcMap directly, or using the *Add Data* button in ArcMap.
7. To reproject the raster to the Swiss coordinate system, open the *Project Raster (Data Management)* tool (browse to *Data Management Tools > Projections and Transformations > Raster > Project Raster*).
8. Select *g100_06.tif* as the *Input Raster*. The *Input Coordinate System* will already be filled in.
9. Save the *Output Raster Dataset* to your working folder as *g100_06_ch1903.tif*.
10. Choose CH1903 LV03 as the Output Coordinate System (*Projected Coordinate Systems > National Grids > Europe > CH1903 LV03*).
11. Choose the *NEAREST Resampling Technique*.
12. Leave the default *Output Cell Size* (100 m) (Fig. S 48).
13. Click *OK*.
14. Click *OK* again to run the tool.

Be patient, this is a large file and it will take some time to complete (~ 10 minutes but depends on your processing system). You will get a pop-up at the bottom right-hand side of your screen when the process has finished.

The resulting projected raster (*g100_06_ch1903.tif*) will be automatically added to the *.mxd. The original CLC06 layer can now be removed from the document as it is no longer needed:

15. Right-click the *g100_06.tif* layer in the TOC.
16. Select *remove*.

6.9.2. Adding vector layer and changing document properties

Since the CLC06 layer covers all of Europe, it should first be clipped to the extent of the required study area using the *Clip (Data Management)* tool so that map rendering is less time consuming in the next steps. This process can also be conducted using the *Extract by Rectangle (Spatial Analyst)* tool. We will use the *commune_boundary_FR.shp* to define the output extent of the clipped land cover raster layer so add the layer to the map now. Note: because the first map layer which was added to the document (*g100_06.tif*) was in the ETRS89_ETRS_LAEA coordinate system, the *.mxd properties automatically take on the properties of that coordinate system. For that reason, you will get a pop-up warning when you try to add layers from the Swiss coordinate system. The warning will state that there may be a problem because a layer with a different coordinate system is being added. Close the warning and change the document properties:

17. Go to menu *View*.
18. Select *Data Frame Properties*.
19. Open the *Coordinate System* tab.
20. Manually change the coordinate system to *CH1903 LV03* (same path as step 10).
21. Click *OK*.
22. Save the *.mxd to keep these changes (*File > Save As...*).

Now the map document coordinate system corresponds to the data being used in the Swiss projection. Next we will clip to the extent of the study area.

6.9.3. Clipping to study area extent

23. Open the *Clip (Data Management)* tool (*Data Management Tools > Raster > Raster Processing > Clip*).
24. Input Raster: *g100_06_ch1903.tif*.
25. Output Extent: *commune_boundary_FR.shp*. The X and Y maximums and minimums will be automatically populated based on the output extent layer.
26. Check the *Use Input Features for Clipping Geometry* option.
27. Save the *Output Raster Dataset* as *g100_06_ch_FR.tif*.
28. Change the NoData Value to 9999 (Fig. S 49).
29. Click *OK*.
30. Turn off the *g100_06_ch1903.tif* and *commune_boundary_FR.shp* layers (uncheck in TOC).
31. Right-click the *g100_06_ch_FR.tif* layer.
32. Select *Zoom to layer* to view the result (Fig. S 50).

6.9.4. Applying a colour map

The layer `g100_06_ch_FR.tif` is now an efficient size for our analysis, but we still do not know what the numbers (raster values) in the raster represent (see Fig. S 50). This is due to the fact that the attribute table of the `g100_06.tif` layer does not include the official CLC06 land cover codes because of a purely technical reason: the codes (50 in total) range from 111 to 999 and cannot be displayed in a single band 8-bit integer raster dataset because the range of values is limited to 0-255. Of course a 32-bit floating-point raster image could be used to display the whole range of values from 111 to 999. However, this would almost quadruple the size of the dataset which would cause problems for download, storage, and analysis. For this reason, the European Environment Agency (EEA) provides a layer file along with the raster image to indicate the code and colour map information which can be easily integrated into ArcGIS.

To add the code and colour map information:

33. Browse to the unzipped land cover folder (`g100_06.tif`).
34. Add the `clc_colortable_92.lyr` file to ArcMap (section 6.3.3.).
35. In the TOC, you should now see a layer called: `lceugr250_00_pct.tif` (which corresponds to the `clc_colortable_92.lyr` file) with a red exclamation point (!) beside it. That means that the layer does not know where the data are located. The codes (e.g. 111, 112, etc.) in this file represent the land covers type from the CLC06 dataset.
36. Right-click the `lceugr250_00_pct.tif` layer.
37. Click *Data*.
38. Now click *Repair Data Source* to tell the layer where the data are located.
39. Browse to the `g100_06_ch_FR.tif` layer.
40. Click *Add*. The red exclamation point beside `lceugr250_00_pct.tif` should have disappeared.

6.9.5. Selecting and labelling land cover values

Now we will remove the land cover values which are not within our study area in order to further optimise the data to fit our needs.

41. Open the properties of the `lceugr250_00_pct.tif` layer.
42. Open the *Symbology* tab.
43. Manually select and remove all values which have a "0" *Count* value (use the Ctrl button on the keyboard to select more than one at a time) (Fig. S 51).
44. Click *OK*. This leaves 14 values in that layer.

Now open the excel file from the previously unzipped folder (`clc_legend.xlsx`) so the land cover names can be added as labels to the codes. This step is not completely necessary but it adds another element to the data. For each code, find the corresponding name ("Label 3") and add it to the TOC by slowly right-clicking the code and pasting the name beside (Fig. S 52). In the following tasks we will make use of the code numbers and names which were just added manually as labels.

6.9.6. Conditional expressions using the raster calculator

To statistically analyse the area covered by three land cover types of interest (arable land, coniferous, and mixed forest) within the 2 km buffers (created in section 6.5.5.1.), we will first create three new raster layers using raster calculator.

45. Open the *Raster calculator* (*Spatial Analyst Tools > Map Algebra > Raster calculator*).
46. Combine *Layers and Variables* and functions until the Raster calculator expression equals "`Con("g100_06_ch_FR.tif" == 12, 1, 0)`" (Fig. S 53) (12 is the raster value for "Non-irrigated arable land" in the CLC06 dataset). The expression is a conditional statement (Con) which literally means: if the value of a pixel from the `g100_06_ch_FR.tif` layer equals 12, assign that pixel a new value of 1. If not, assign a value of 0. This will create a binary raster.
47. Specify an output raster, e.g. `lc_class211.tif`, which denotes that the new layer will represent the 211 (Non-irrigated arable land) land cover code.
48. Click *OK*.
49. Repeat steps 45 to 48 with the following raster values: 24 (replaces 12 in the equation in step 46.) (class 312 as the output, Coniferous forest) and 25 (class 313, Mixed forest).

The newly created raster images contain zones with the value 1 (where the *Raster calculator expression* was true, i.e. the land cover represents the non-irrigated arable land category) and 0, where the expression was false (i.e. the land cover does not represent the non-irrigated arable land category).

6.9.7. Zonal statistics of land cover values within buffers

With this binary classification, we can now do a simple statistical analysis of the land cover within each buffer polygon layer. Below, the *Zonal Statistics as Table* tool will be used to summarise the values of the land cover layer within the buffers created in section 6.5.5.1. and output the results into a table. Specifically, we will calculate the mean percentages of non-irrigated arable land, coniferous forest, and mixed forest within a 2 km radius of the honey bee colony locations.

50. Open the *Zonal Statistics as Table Tool* (*Spatial Analyst Tools > Zonal > Zonal Statistics as Table*).
51. Input raster or feature zone data: `buffer2000.shp` (browse to or add to `*.mxd`).
52. Zone field: FID (Unique identifier).
53. Input value raster: one of the newly created binary raster images (e.g. `lc_class211.tif`).
54. Output table: `stats211`.
55. Check the *Ignore NoData in calculations* option.
56. Choose the Statistics type *MEAN* (Fig. S 54).
57. Click *OK*.
58. Open the *Results* window (*Geoprocessing > Results*) and double click the *Zonal Statistics as Table* option (since that was the last process completed).

59. Repeat steps 50 to 57 for the other input rasters by altering the input dialog for the classes 312 and 313 (choosing appropriate filenames for the results).

Now look at the table results in the TOC (Fig. S 55). If you cannot see the tables in the TOC, make sure you are in *List by Source* view instead of *List by Drawing Order* (section 6.3.4.). In each table you will see columns for Rowid, FID (unique identifier corresponding to buffer ID), COUNT (number of pixels of particular land cover class inside the buffers), AREA (calculation of square meters of land cover class within the buffers), and MEAN (in percentage). In Fig. S 55, the mean values directly correspond to the percentage of non-irrigated arable land within each buffer (uniquely identified by its FID value).

6.9.8. Joining statistical information to attribute table

Now we will do a table join to connect the calculated statistical information directly to the colony_locations.shp shapefile based on the unique identifier in both the statistics table and the attribute table of the colony locations layer. By doing this, statistical information will be directly linked to the colony locations attribute table. This allows for the symbolisation and visualisation of statistical information on the map based on the geographic location of the colonies. For example, in section 6.10.4. we will symbolize each colony based on its statistical properties.

60. Right-click on the colony locations layer in the TOC.
61. Select *Joins and Relates*.
62. Click *Join*.
63. Select the option to *Join attributes from a table* (Fig. S 56).
64. Choose the FID as the fields on which to base the join with the stats211 table.
65. *Keep all records*.
66. Click *OK*.
67. Open the *Attribute table* for buffer2000.shp and scroll over to the right. You will see the values from the stats211 table have been added to the end. Since we are only interested in the *MEAN*, turn off the other fields (*right-click column name > Turn field off*). For table organisation purposes, other fields can also be turned off (this is not permanent – to undo go to *Table Options* (top left corner of table) and *Turn all fields on*).
68. To distinguish this *MEAN* column (211) from the other 2 other mean value columns (312 and 313), which we will add in the next steps, let's rename the column (*Right-click column name > properties*).
69. In the *Alias* field, change the name to "211MEAN".
70. Click *OK*.
71. Repeat 60-70 for the 312 and 313 statistics tables.

6.9.9. Adding and populating a new field in attribute table

Now, to obtain a value for all of the other land cover classes besides 211, 312, and 313, we will create a new column in the table and then calculate the values of "other" land cover values inside each buffer.

72. Open the *Table Options* for the colony_locations layer.
73. Click *Add Field*.
74. *Name*: LC_other.
75. Choose the *Type* Float.
76. Use the field calculator to populate this column. *Right-click* on LC_other field name.
77. Select *Field calculator*. Fill out the dialog box according to Fig. S 57 with the equation: $1 - ([stats211:MEAN] + [stats312:MEAN] + [stats313:MEAN])$ which calculates the percentage of "other" land cover types in relation to the three we have already used.
78. You will end up with a table similar to the one in Fig. S 58. We will use these four new fields later in the Map creation section (6.10.).

Note: as you can see in Fig. S 58, there are "<NULL>" values for FID 16. This seems to be a glitch in the *Zonal Statistics as Table* tool. There are ways this can be fixed in the table but we will not deal with them now.

6.9.10. Visualisation of attributes using graphs and charts

To visualise the statistical data another way, graphs and charts can also be created in ArcMap. To create a graph similar to that in Fig. S 59., go to *View > Graphs > Create Graph*. Use the mean values for 211, 312, 313, and LC_other. In the next section, a final map will be created showing the case study results.

6.10. Map creation

Map creation is one of the main functionalities in ArcMap. Here we will give a brief tutorial about how to create a map as the final product of the GIS analysis. This task assumes that all layers created in the previous steps are already in the map document (including the results of the case study).

6.10.1. Data view vs. layout view

In ArcMap there are two different views: one for viewing, manipulating, and analysing data (Data View, Fig. S 60), and one for creating the final map product (Layout View, Fig. S 61). To switch between the two, toggle the buttons at the bottom left hand corner of the data frame (map display, see Fig. S 60). The toolbars used in each of these views can be confusing as there are multiple tools for zooming. The *Tools* toolbar is used for zooming in and out of the data frame, thus the actual data, and the *Layout* tools toolbar is used to zoom in and out on the final map document. See Figs. S 60 and S 61 to help understand the differences between these two views and also the different toolbars.

6.10.2. Symbology

The layer symbology can be changed within the properties of each layer under the *Symbology* tab. Depending on the type of data you want to symbolize, there are various options. For example, layers can

be symbolized based on one set of features (Features), categories of attributes based on unique values or unique values using many fields (Categories), or quantities of attributes (Quantities). As an example, we will use the *commune_boundary_FR* layer and change the symbology so that each commune is represented by a different colour.

To change symbology to represent unique features:

1. Right-click *commune_boundary_FR* layer.
2. Select *Properties*.
3. Select *Symbology*.
4. Select *Categories*.
5. Select *Unique values*.
6. For the *Value Field* choose the attribute to be symbolized. In this case it is GEMNAME.
7. Click the *Add All Values* button.
8. Click *OK*.

The results show each commune represented by a different colour (Fig. S 62).

6.10.3. Labels

Labels can be automatically added for any layer.

To add labels to a layer:

1. Right-click the *commune_boundary_FR* layer.
2. Click the *Labels* tab.
3. Check the *Label features in this layer* option.
4. Label field: GEMNAME.
5. Click *OK*.

Now the name of each commune can be seen (Fig. S 63).

6. To make the label larger or change the font *Properties > Labels*.

6.10.4. Advanced symbolization

In this step, the statistical results of the case study will be symbolized using pie charts.

1. To begin, open the layer properties of *colony_locations.shp*.
2. Open the *Symbology* tab.
3. Choose *Charts* and make sure *Pie* is selected.
4. Add the *MEAN* attributes (including *LC_other*) to the *Symbol/Field* box. Change the colours to correspond with the original land cover values (Fig. S 64).
5. Click *OK*.
6. Now label the colony locations to denote the FID identifier number (see above).

The map should now look something like Fig. S 65, which is the data in *Data View*. Maybe you will notice that FID 16 is missing. Because of the error we encountered earlier, it did not get symbolized or labelled.

6.10.5. Final map preparation

Now we will put the finishing touches on the map in *Layout View*. For the final map the pie charts and communes will be displayed with the background of the DEM and the hillshade for terrain visualization.

To finalize the map:

1. Turn on the *commune_boundary_FR*, *colony_locations* (symbolized as pie charts), *hillshade*, and *DEM* layers in the TOC.
2. Go into *Layout View* (bottom left hand corner of the map window).
3. The page size is automatically set to normal printing page size. To change the page size, go to *File*.
4. Select *Page and Print Set-up*.
5. Uncheck *Use Printer Paper Settings*.
6. Insert your own values for the width and height of the page (22 x 24 cm were used here).
7. Click *OK*.
8. Rescale the data frame (dotted green line) to fit inside the page border (solid black). Leave some white space between the data frame and the page border to insert a grid later.
9. Right-click the *colony locations* layer.
10. Select *Zoom to layer* to focus the map on this layer. Remember to use the standard tools to zoom in and out on the data, and the layout tools to zoom in and out on the page.
11. Play around with the transparency values of the layers to make a nice end product. Go to *Properties*.
12. Select the *Display* tab.
13. Insert a value between 0 (no transparency) and 100 (completely transparent).

6.10.6. North arrow, scale bar, legend, title, text

To add a north arrow:

1. From *Layout view*, click *Insert* (main menu).
2. Click *North arrow*.
3. Select the style of the north arrow.
4. Click *OK*.

To add a scale bar:

1. Click *Insert*.
2. Select *Scale bar*.
3. Choose the style.
4. Click *Properties*.
5. Select the number of divisions and units.
6. Click *OK*.
7. Click *OK* again.
8. Double-click *Scale* to change the properties.

To add a legend:

1. Click *Insert*.

2. Select *Legend*.
3. Choose the layers to add to the legend.
4. Click *Next*.
5. Choose the legend title.
6. Click *Next*.
7. Choose a border, background, or shadow.
8. Click *Next*.
9. Click *Next* again.
10. Click *Finish*.

To add a title or other text:

1. Click *Insert*.
2. Click *Text*.
3. Type the text.
4. Hit *Enter*.
5. Double-click on the text box to open the properties.
6. Change the size and font.
7. Click *OK*.

Once added to the map, you can double-click on any feature in the layout view to open its properties. Also, the scale bar and legend are linked directly to the map, therefore they change as the map changes. For example, the scale bar will adjust to the scale of the map, and the legend items will adjust if the symbologies or names of layers change in the TOC. To adjust these features manually they must first be converted into graphics and ungrouped.

To manually change the legend:

1. Right-click the legend.
2. Select *Convert to graphics* (this unlinks the feature from the map).
3. Right-click the legend again.
4. Select *Ungroup* to have the ability to select individual features and edit them (some features required a second "ungrouping" to be editable, e.g. the symbols and labels).
5. Select the item to edit.

Note: once the item has been converted to graphics, there is no going back (you would have to insert the item again from scratch) and, the item is no longer dynamically linked to the map contents. Therefore changing layers and map scales will no longer change legend items or scales. It is recommended that conversion to graphics is the final step in the map creation process.

6.10.7. Drawing toolbar

The *Drawing* toolbar is useful for adding graphics such as shapes, text, and lines to the map.

To open the toolbar:

1. Go to *Customize*.
2. Select *Toolbars*.
3. Select *Draw*.

6.10.8. Adding a grid

To add a numbered grid around the map:

1. Go to *View* (main menu).
2. Select *Data Frame Properties*.
3. Select *Grids*.
4. Select *New Grid*.
5. Select the *Measured Grid* option (this is for projected coordinate systems (meters)), *Graticule* is for Geographic coordinate systems (latitude/longitude)).
6. Choose the *Labels only* option.
7. Click *Next*.
8. Here you could change the axes and labels, click *Next*.
9. Click *Finish*.
10. Click *OK*.

To adjust the properties of the grid, go back into the *View > Data Frame Properties > Grids* menu. Here, there is also the option to convert the grid to graphics in order to manually adjust it. See Fig. S 66 for the final map in ArcMap.

6.10.9. Exporting a map

To export the final map product:

1. Go to *File*.
2. Select *Export Map*.
3. Name it and choose the format (JPEG, PDF, etc.).
4. Choose the resolution (high quality resolution is 300 dpi (dots per inch) and draft quality is normally 96 dpi; also line art (contour lines, labels, ...) should be at 600 dpi and raster graphics at 300.).
5. Click *Save*.
6. Browse to the exported map.
7. Open it to view the results and see if any changes are needed (see Fig. 67 to view the exported map).

6.10.10. Cloud mapping and ArcGIS Explorer

Recently, ArcGIS has created a cloud mapping platform online which allows users to share their maps and data with others, access their maps online, on their desktop, and on mobile devices through the use of the cloud. On ArcGIS online, users can create maps by adding their own data, choose from different base layers, and use other people's shared data that has been uploaded to the site. This site is useful for map creation when you do not have access to the ArcGIS software, but want to make a basic map. All you need is an ESRI Global Account which is free to sign up for. For more information about ArcGIS online visit <https://www.arcgis.com/home/>.

ArcGIS Explorer is an application that can be downloaded for the purposes of exploring, visualising, and sharing geographic information. Users can also access ArcGIS' basemaps and layers,

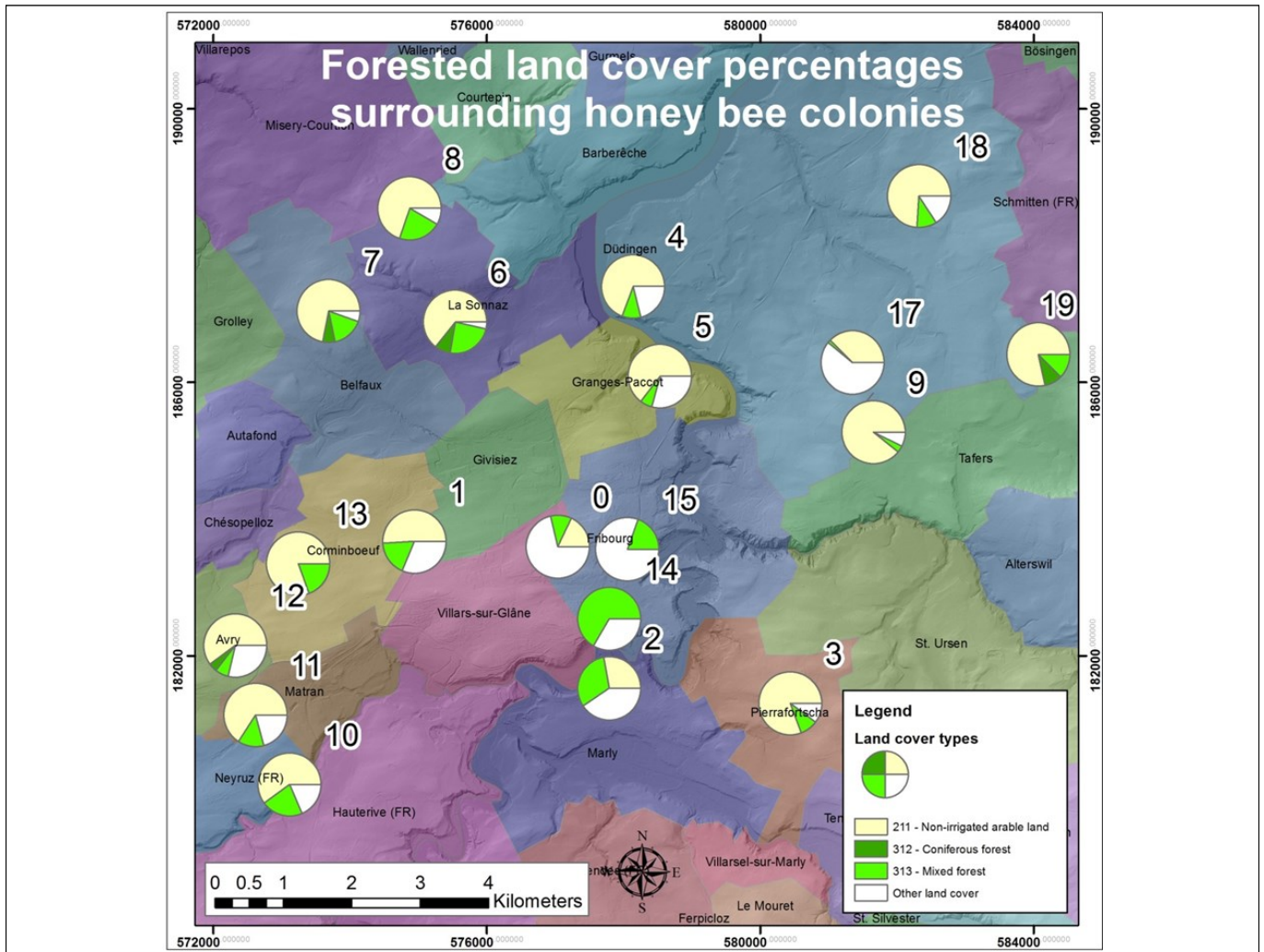


Fig. 67. The final map exported as a JPEG file. Reproduced with permission of Swisstopo (BA13016).

customise maps by adding data, photos, reports, and videos. Basic spatial analyses can also be performed. ArcGIS Explorer can be downloaded from <http://www.esri.com/software/arcgis/explorer>.

7. Using Quantum GIS (version 1.8.0.)

This section provides a brief hands-on tutorial as an introduction to Quantum GIS (QGIS) and shows examples of how open source GIS can be used instead of proprietary software for the same research applications as demonstrated in the previous chapter. QGIS is licensed under the GNU General Public License (<http://www.gnu.org>) and is an official project of the Open Source Geospatial Foundation (<http://www.osgeo.org>). This tutorial is based on QGIS version 1.8.0. "Lisboa" that was the latest stable release at the end of 2012 and runs on the 64-bit Microsoft Windows 7 operating system. Detailed information about QGIS, its functionalities, and the installation procedure on different platforms is well documented on the project

website (<http://www.qgis.org>) and in the manual to version 1.8.0 (QGIS Development Team, 2013).

7.1. Main components of QGIS

QGIS includes the main program QGIS Desktop, QGIS Browser for data management, and a variety of optional plugins that provide specific functionalities.

7.1.1. QGIS Desktop

QGIS Desktop is the main interface for data collection, analysis, and presentation on the client-side and is similar to ArcMap (see section 6.1.1.). The language of the GUI is chosen automatically by the system defaults, but it can be changed within the menu *Settings > Options > Locale*. Most of the menus and symbols (Fig. S 68) are self-evident and should be easy to use for anyone with basic knowledge in GIS techniques, but in particular the menu "Plugins" is different than other software and will be discussed more in detail (see 7.1.3.). Projects (equivalent to map documents within ArcGIS, see section 6.3.1.) saved within QGIS are stored using the XML-Standard (Extensible Markup Language, machine and human-readable) and with the extension *.qgs.

Table 4. QGIS Plugins and Repositories list used or mentioned in this tutorial.

Plugin name	Repository
Add Delimited Text Layer (see section 7.3.3.1.)	Core plugin, automatically installed with QGIS (can be enabled and disabled in the Plugin Manager)
fTools (see section 7.6.)	Core plugin, automatically installed with QGIS (can be enabled and disabled in the Plugin Manager)
Spatial Query (see section 7.4.1.)	Core plugin, automatically installed with QGIS (can be enabled and disabled in the Plugin Manager)
Raster Terrain Analysis Plugin (see section 7.7.2.)	Core plugin, automatically installed with QGIS (can be enabled and disabled in the Plugin Manager)
GDAL Tools (see section 7.5. and 7.7.)	Faunalia Repository (http://www.faunalia.it/qgis/plugins.xml)
qgSurf (see section 7.8.3.)	QGIS Official Repository (http://plugins.qgis.org/plugins/plugins.xml)
Chart Maker Plugin (see section 7.9.)	QGIS Contributed Repository (http://pyqgis.org/repo/contributed)
SEXTANTE (see section 7.8.2.)	QGIS Official Repository (http://plugins.qgis.org/plugins/plugins.xml)
QGIS Cloud Plugin (see section 7.9.5.)	QGIS Official Repository (http://plugins.qgis.org/plugins/plugins.xml)
XyTools (see section 7.3.3.1.)	QGIS Official Repository (http://plugins.qgis.org/plugins/plugins.xml)

7.1.2. QGIS Browser

Starting in version 1.7., a new feature has been added to QGIS: The QGIS Browser (Fig. S 69). This browser is a data management program similar to ArcCatalog (see section 6.1.2.), simplifies file navigation within the file system, and provides preview options for various file types. Items can be easily added to the Map View of QGIS Desktop by drag and drop.

7.1.3. Plugins

In addition to its core functionalities, QGIS can be extended modularly with additional features and functionalities, downloadable from so-called repositories through the internet. By the end of 2012, about 175 plugins were listed on the project website provided by various authors (<http://plugins.qgis.org/plugins>). Because the application is open source, everyone is authorized to change or add features for special purposes by programming in the languages C++ or Python. Often, popular external plugins that have a big impact on the user community are implemented into the core functionalities of QGIS in the following release.

Plugins can be loaded and unloaded from the main menu *Plugins > Fetch Python Plugins* (Fig. S 70) from various internet repositories directly into the QGIS Desktop. Some of the plugins might require additional software packages or libraries, or are still marked as “experimental”, indicating an early stage of development.

Within this tutorial the plugins listed in Table 4 will be used, so it is recommended to install them now:

1. Open QGIS, go to the *Start Menu*.
2. Go to *All Programs*.
3. Open the *Quantum GIS Lisboa* folder.
4. Select *Quantum GIS Desktop 1.8.0*.
5. From the main menu go to *Plugins*.
6. Select *Fetch Python Plugins*.

7. Open the *Repositories* tab.

8. Click *Add...* and type in the name and URL for the “Faunalia Repository” corresponding to Table 4.

9. Click the checkbox to enable the repository.

10. Click *OK*.

11. Verify if the “Faunalia Repository” is listed and if the connection works correctly (indicated with a green icon).

12. Repeat steps 8 to 11 also for the Repository called QGIS “Contributed Repository” (see Table 4).

13. Switch to the tab *Options*.

14. Activate the checkbox *Check for updates on startup*.

15. Set the *allowed plugins* to *Show all plugins, even those marked as experimental*.

16. Switch back to the tab *Plugins* within the QGIS Python Plugin Installer.

17. Filter for a plugin name (e.g. “GdalTools”) and select it in the list.

18. Click *Install/upgrade plugin*.

19. Repeat the steps 17 and 18 for all these Plugin names:

“GdalTools”, “qgSurf” and “Chart Maker”.

20. Close the QGIS Python Plugin Installer.

To remain focused on the most important functionalities for your daily work, it is recommended to make use of the Plugin Manager (Fig. S 71):

1. Open *Plugins*.
2. Select *Manage Plugins*.
3. Click *Select All*.
4. Click *OK*.

For more detailed information about managing and troubleshooting QGIS plugins on different platforms, see the QGIS user guide (QGIS Development Team, 2013).

7.2. Navigating the software

One motivation for the development of QGIS was to provide a user friendly GIS software with a simple and straightforward graphical user interface (GUI, QGIS Development Team, 2013). This was also one major motivation for why we chose QGIS as the representative for open source GIS within this tutorial.

7.2.1. Help menu and tooltips

The *Help* menu is placed at the right of the main menu bar in *QGIS Desktop* (Fig. S 68) or can be opened with the shortcut *F1* (on Windows). The majority of the functions and tools are well documented in the user guide (QGIS Development Team, 2013) and additional information is accessible at the QGIS project website (<http://www.qgis.org>). Useful information is provided by the tooltips (that usually appear when the mouse cursor is placed over an icon for a few seconds) indicating the name or functionality of the buttons and plugins. In addition, several functions and plugins have their own help button like the example in Fig. S 70. Thanks to a huge effort from the community, the GUI and large parts of the help menu have already been translated into many different languages.

7.2.2. User guide and documentation

All documentation for QGIS can be found on the project website <http://www.qgis.org>, divided into the two categories "Manuals" (containing user guides and tutorials) and "Developer" (providing programming help for developers). The official manual, the QGIS user guide (QGIS Development Team, 2013) cited in this tutorial, was released on the 15th of January 2013 and might have changed since then.

7.3. Adding data and working with different file formats

Adding geodata to QGIS Desktop is as easy as with ArcMap (see section 6.3.): a variety of file formats can simply be dragged and dropped, for example, from a folder within the file system directly into the *Map Legend* panel on the left of QGIS Desktop or loaded from the *Manage Layers* toolbar. The following hints and remarks will provide a start-up aid for users new to GIS and for some specific data types.

7.3.1. Setting a coordinate system and saving the new QGIS project (*.qgs)



Similar to the ArcGIS section (6.3.1.), it is important and recommended to first set the coordinate system according to the data used for the analysis or the target projection of the final map product, respectively (Fig. S 72):

1. Go to *Settings*.
2. Select *Project Properties*.

3. Select *Coordinate Reference Systems (CRS)*.
4. Activate the checkbox on top called *Enable "on-the-fly" CRS transformation*.
5. Select the projection called *CH1903 / LV03* with the EPSG-code *21781* within the list of the *Coordinate reference systems of the world* (Group *Swiss. Obl. Mercator*, see Fig. S 72) with a double-click.
6. Click *OK* to apply these settings and close the *Project Properties* dialog.
7. Verify by checking if the EPSG-code 21781 is written in the *Status Bar* (see Fig. S 68).

Note: This step is very important for the rest of this tutorial, because choosing the wrong CRS may lead to various problems in geoprocessing.

Advanced users who deal with a variety of different projections might appreciate the possibility to filter the list of all coordinate systems (Fig. S 72) by names or the identification number of the EPSG Geodetic Parameter Dataset (<http://www.epsg-registry.org>). Switching back to the *General* tab of the *Project Properties*, the *Layer units* will be now set to meters, because the Swiss oblique Mercator projection uses metric units.










8. Save the new project and settings, go to *File*.
9. Select *Save Project As*, or click the button  to the desired destination folder (A QGIS project file with the extension *.qgs will then be created).
10. It can be reopened directly by a double-click on the file or within the QGIS main menu *File > Open Project* or the *open project* button  from the *File* toolbar.

7.3.2. Add data to the project

Most of the functions to add and remove data or to change layer properties and appearance can be accessed through the main menu *Layer*. Of particular interest are the functions (listed in Table 5) contained in the *Manage Layers* toolbar:

Only data of the appropriate type (see sections 2.2.1. and 2.2.2.) will be selectable as a source for adding vector or raster data, respectively. In case the data type or the file extension is unknown, try to drag and drop the files directly from the source folder into the *Map Legend* in QGIS Desktop (Fig. S 68). Take into consideration that some common file formats consist of multiple files and that the main file has to be chosen (e.g. the file with the extension *.shp for a shapefile or the *.tif for a raster in GeoTIFF format, respectively, see also section 3.1.). Due to the Geospatial Data Abstraction Library for raster data translation GDAL (<http://www.gdal.org>) and the OGR Simple Feature Library (<http://www.gdal.org/ogr>) QGIS has excellent data interoperability capabilities and almost every geodata file format from any source can be loaded into the *Map View*.

Table 5. The most important functions of the *Manage Layers toolbar*. This toolbar can be enabled and disabled by the main *menu View > Toolbars > Manage Layers*.

Menu Entry Layers	Icon	Purpose
New		Creates a new layer without content (shapefile or SpatialLite database)
Add Vector Layer		Add new vector layer(s) (see section 7.3.3.)
Add Raster Layer		Add new raster layer(s) (see section 7.3.3.)
Add PostGIS Layers		Manage connections to PostGIS databases, load PostGIS layers and tables (http://www.postgis.org/)
Add WMS Layer		Add and manage layers from Web Map Services (http://www.opengeospatial.org/standards/wms)
Add WFS Layer		Add and manage layers from Web Feature Services (http://www.opengeospatial.org/standards/wfs)
Remove Layer		Remove layer(s) (see section 7.3.3.1.)
Add Delimited Text Layer		Import delimited text files (see section 7.3.3.)
Create new GPX Layer		Create a GPX file for the use in Handheld GPS devices (see section 7.3.3.2.)

7.3.3. Importing vector and raster data

Now it is time to add some data to the new empty QGIS project:

1. Choose *Layers*.
2. Select *Add Vector Layer*.
3. Browse to the source folder of your Geodata (for example select *commune_boundary_FR.shp*, see section 5.3.).
4. Press *Open* to load the shapefile.

As an intermediate result, a rectangle full of polygons (see section 2.2.1.) representing different administrative districts, called communes, within the canton of Fribourg (western Switzerland) appears (Fig. S 73).

In the same way, but with the *Add Raster Layer* function, a DEM (see section 3.2.4.) can be added to the map:

1. Open *Layers*.
2. Select *Add Raster Layer*.
3. Browse to the source folder of your Geodata (for example select *ASTER30_WGS84.tif*).
4. Click *Open* to load the DEM into QGIS.

A rectangular greyscale raster image appears around the city of Fribourg in western Switzerland (Fig. S 73). If the raster is not visible, please check that the "on-the-fly" *CRS transformation* is enabled within the dialog accessible through the menu *Settings > Project Properties > Coordinate Reference Systems (CRS)* (see also Fig. S 72).

If the raster image is displayed in a uniform grey, the display options must be adapted:

5. Open *Layer*.
6. Click *Properties*.
7. Select the *Style* tab.
8. Click *Load* in the *Load min/max values from band* option.
9. In the *Contrast enhancement* option, choose *Stretch to MinMax*. The raster values range from 407 (black) to 883 (white), that represents the altitude above sea level in meters.
10. Click *OK*.

The new data will be added to the top of the map, thus probably hiding some other content behind it (the display order is defined by the hierarchy in the *Map Legend*). Considering the current map display, we see that the raster image has a smaller extent than the vector layer and only few details are visible at this scale. To zoom to the region of interest around Fribourg, suitable operations are:

- Using the *Zoom* and *Pan* icons in the *Map Navigation toolbar* or the same functions in the *menu View*



- Right-click on the raster image in the *Map Legend* (in our example called *ASTER30_WGS84*) and choose the option *Zoom to layer extent*.
- Zoom with the mouse wheel placing the cursor at the centre of the area of interest.

Now the topography and the Sarine River crossing the city of Fribourg from south to north are visible (Fig. S 74). First of all, from this step we learn that QGIS has several tools for similar applications, and every user will find and choose the most efficient manner to achieve their goals. Second, it is beneficial to use (or even try) the right mouse button, for example to set the *Map View* exactly to the extent of one specific layer or to the access the *Layer Properties*. Advanced users might be comfortable using the mouse wheel to change the zoom level while other tools stay activated (e.g. during digitisation).

7.3.3.1. Add delimited text layer (*.txt, *.csv)

In this section, a simple text file will be added to QGIS to visualize and analyse it spatially (for more information about this refer to section 6.3.3.1.):

1. Open *Layer*.
2. Choose *Add Delimited Text* or click the appropriate button from the *Manage Layers toolbar* (Table 5).

3. Choose the source text file (in our case the comma delimited textfile `points_table.csv`).
4. Give a name to the output layer (e.g. `bees_colony_locations_tab`).
5. Select the appropriate delimiters (e.g. semicolon or comma) and the columns containing the coordinates in East (X) and North (Y) according to Fig. S 75.
6. Click *OK*.
7. Choose the CH1903/LV03 projection from the CRS selector list.
8. Click *OK*.
9. Go to *File*.
10. Click *Save Project*.

As a result, the honey bee colonies are shown as point information on top of the *Map View* (Fig. S 76). It is important to note, that this layer is loaded into QGIS and available for any display and map creation purpose and also some basic analysis, but not physically stored as geodata in the file system. To get the full functionality of a point vector file, save this layer e.g. as a shapefile by performing the following steps:

1. Right-click the layer in the *Map Legend* (Fig. S 68).
2. Choose the *Save as* option in the context menu.
3. Select a file format (in our case it will be an ESRI Shapefile).
4. Select a target destination folder within the file system (e.g. with the filename `bees_colony_locations.shp`).
5. If special text characters are included, choose an encoding that is suitable (e.g. for Western Europe utf-8 or latin1 are good options).
6. Select the correct CRS (in our case it is CH1903 / LV03).
7. Enable the option *Add saved file to map* (Fig. S 77).
8. Click *OK*.

A message ("Export to vector file has been completed") will appear and the layer will be added on top of the *Map Legend*.

9. Select the old text file from the *Map Legend* using a left mouse click.
10. Press the button *remove layer(s)* (see Table 5) to remove it from the project – we will only need our newly created shapefile for all future steps.

Using the *plugin* called "XyTools" (Tab. 4) it is also possible to import Microsoft Excel or OpenOffice spreadsheets, similar to the procedure presented in section 6.3.3.1.

7.3.3.2. GPS and KML data, working with different coordinate systems

Other important functionalities of modern GIS are those to import and export GPS data (e.g. those acquired by handheld GPS devices), and the transformation between different coordinate systems. Because the GPS eXchange Format *.gpx is common and integrated within the OGR library (see section 7.3.2.), the import of existing GPS data is as simple as adding other vector data (see section 7.3.3.). Assuming that

our point vector layer added in the previous step represents colony locations of honey bees we would like to locate in the field, this vector layer needs to be exported to a new *.gpx-file to be uploaded onto a handheld GPS device. This can be done with the same function used to save a layer to a new shapefile (Fig. S 77), but modified settings:

1. Right-click on the layer in the *Map Legend*.
2. Select *Save as*.
3. Choose the GPS eXchange Format (supported by a majority of GPS devices).
4. Set the target coordinate system to "WGS84" (because GPS devices are natively working in World Geodetic System 1984).
5. Enable the option *Skip attribute creation* (because we only need the coordinates for a stakeout of the colony locations in the field, without any attributes).
6. Click *OK* and verify if the new file (e.g. with the file name `bees_colony_locations_WGS84.gpx`) has been created within the chosen destination folder.

Behind this two very important technical GIS functionalities are working: first, the translation from a source file format (*.shp) to a target file (*.gpx) format and second, a precise transformation between two different coordinate systems, even with different map units. If you have a software like Google Earth for instance, you can easily verify if the coordinate transformation to WGS84 worked correctly (if you do not have Google Earth installed, you can skip this paragraph, or download the software from <http://www.google.com/earth/index.html>).

1. Open Google Earth.
2. To open the *.gpx-file in GoogleEarth, go to *File*.
3. Click *Open*.
4. Browse to the location of *.gpx file.
5. Beside the *File name* box, choose the *Gps* option from the dropdown menu.
6. Click *Open*.
7. The GPS data Import dialog window will appear asking if KML tracks should be created from the GPS data. Check the options *Create KML Tracks* and *Adjust altitudes to ground height* (with this function, all elements are attached on top of the elevation model behind GoogleEarth and you are sure that all features will be visible) and confirm with *OK*.
8. Google Earth will do a file format conversion that results in a new temporary layer named "GPS device" in the panel *Places > Temporary Places*. The new created placemarks in Google Earth should be at the same location as in the QGIS project.
9. Right-click on the layer *GPS device*.
10. Click *Save Place As* to save this temporary layer to the file system in the KML format (Fig. S 78, make sure to choose KML instead of the zipped KMZ format).

The Keyhole Markup Language (KML) is another file format supported by the OGR library. It provides great possibilities to share

spatial information of vector based geodata with people who are not familiar with GIS software, since almost everybody can handle software like Google Earth. Of course it is also possible to import the KML file back to QGIS. We will see if the coordinate transformation from WGS84 back to the Cartesian CRS of Switzerland works fine:

1. Just drag the KML file from its data source to the *Map Legend* in your QGIS project.
2. By activating and deactivating the checkbox to the left of the layers you can check if the geometries are congruent.

If there is a lateral shift between the point layers or an error in scale, the option "on-the-fly" CRS transformation was probably not enabled – you can fix this by navigating to the main menu *Settings > Project Properties* where you choose the second tab *Coordinate Reference Systems (CRS)*.

7.3.4. Layer organisation and navigation

Managing layers with QGIS is very similar to ArcGIS, thus the following hints are complementary to sections 6.3.4. and 6.3.5:

- The drawing order of one specific layer relative to the others can be changed in the *Map Legend* (Fig. S 68): click on the layer and hold the left mouse button to move layers upwards or downwards in the hierarchy.
- Within a large project it is recommended to make groups (right-click on the *Map Legend > Add New Group*), to be more flexible to turn a whole group of layers on and off together, for instance, or to get more space in the layer hierarchy by collapsing multiple legends.
- To avoid losing the most important buttons and menus, have a look at the main menu *View > Panels and View > Toolbars*. Here you can enable additional panels to the QGIS GUI (e.g. the *Overview* or the *QGIS Browser* window) and show or hide several toolbars and buttons (the most essential toolbars are *Attributes*, *File*, *Manage Layers* and *Map Navigation*).

To achieve a good visualization result, changes in the layer *Layer Properties* are often required – the topic of the following section.

7.3.5. Layer properties

The properties of one specific layer can be accessed by the main menu *Layer > Properties*, a right-click on the layer name and choosing the entry *Properties* in the context menu or simply by double-clicking the layer name. The *Layer Properties* might vary between different file formats, but every layer will at least have tabs for *Style* options, *General settings* and provide *Metadata* information. Let's first have a look at the *Metadata*, the information about the data: opening the *Metadata* for the layer *commune_boundary_FR.shp*, the following information appears (Fig. S 79):

Apart from the file format, data source, and geometry type, we can also learn something about the number of features ($n = 51$), the


coordinate reference system (CRS) used for projection and the spatial extent (minimal and maximal values for X and Y). The current administrative districts are digitized as polygons, displayed with an opaque colour fill. To combine them with our elevation model, the fill colour could be removed and the border set to a bright colour:

1. Open the *Layer Properties* window by a method of your choice (see above).
2. Switch to the tab *Style*.
3. Click the button *Change* to the left and a further window with *Symbol properties* will open.
4. Select an appropriate *Symbol layer type* in the *Symbol properties* window (dropdown-menu on top) (Fig. S 80). By default, polygon layers are visualized by a "simple fill" with a uniform colour for the fill area and black lines representing the polygons borders. Change the layer type e.g. to *Outline: simple line*.
5. Fill with a colour of your choice.
6. Click to close the *Symbol properties*.
7. Click *Apply* to implement the changes.
8. Close the *Layer Properties* with *OK*.
9. Move the polygon layer one level higher in the *Map Legend* on top of the elevation model.

7.4. Data selection and editing

This section presents the most important selection queries and editing tasks using different techniques in QGIS.

7.4.1. Spatial query and select by location

Similar to ArcGIS (section 6.4.1.), different functions exist to obtain information for defined locations: The *Identify Features* button  is the same as the *Identify* tool of ArcGIS (see section 6.4.1.) and is used to obtain information about specific pixel values within a raster image or to look at the attribute values of a vector feature. Before applying the *Identify Features tool*, it is necessary to activate and select the appropriate layer in the *Map Legend*. In addition, various spatial operations are provided within the main menu *Vector*. Of particular interest is the function *Spatial Query* that allows more advanced queries by using vector geometries. To demonstrate this functionality with QGIS we will ask for all communes that contain at least one honey bee colony.

1. Choose *Vector* from the main menu.
2. Select *Spatial Query* (a dialog window will appear).
3. Select the layer *commune_boundary_FR.shp* as *Source Features* and the point vector file with the honey bee colonies as *Reference Features*.
4. Choose the operator *Contains* to be applied between these two features.
5. Choose to create a *New Selection* (alternatively, it could be added to or removed from an existing selection).

6. Click *Apply* and close the dialog, if the result looks similar to Fig. S 81.


Intersection operations can also be applied with the help of the function *Select by location*:

1. Go to *Vector*.
2. Choose *Research Tools*.
3. Select *Select by location*.
4. Choose the settings according to Fig. S 82 to achieve similar results as displayed in Fig. S 81.

In practice, spatial selection operations are frequently used to assign attributes of one layer to another layer and for raster calculation tasks or modelling tasks.

7.4.2. Select by attributes

Let's have a look at the result of the spatial query from the last section: In total eleven features were highlighted (that means selected) within the layer *bees_colonies_locations.shp*. So far so good, but what if the research question was to get the names of all communes containing honey bee colonies? To achieve this goal:

1. Right-click the *commune_boundary_FR.shp* layer.
2. Choose *Open Attribute Table* or use the button  within the *Attributes* toolbar.

It is written in the headline of the *Attribute table* that the selected layer contains 51 entries in total (representing communes).

Because they are topologically correct (see section 2.1.), none of these communities intersects with another and all the borders are congruent (that means that there are no blank "islands" in between).

3. To focus on the selected features within a large dataset, use the checkbox named *Show selected only* within the *Attributes table* (Fig. S 83). Browsing to the right within the different attributes, within the column called "GEMNAME", the name of each community is given.
4. The *Attribute table* can stay open while other functions are performed, e.g. during digitizing or editing tasks.

Assuming that the goal to produce a map that shows only the municipalities of the canton Fribourg, the following workflow can be applied:

1. Right-click the *commune_boundary_FR.shp* layer.
2. Select *Query*.


The *Query Builder* dialog opens (Fig. S 84). The attribute "KANTONSNR" contains an ID that represents the canton in Switzerland and in the case for Fribourg it is 10. So it is now our goal to restrict the features by means of a formula like "KANTONSNR" = 10. QGIS will then perform a restriction on the polygons displayed similar to an SQL Selection-Query by the use of a "where clause" (http://www.w3schools.com/sql/sql_where.asp).


3. Try to rebuild the formula mentioned above by activating the options *Fields*, *Operators* and *Values* (otherwise it can also be written manually).
4. Confirm the query with *OK*.
5. Right-click on layer and *Zoom to the layer extent*.

Two polygons in the north-west outside of the canton of Fribourg will have disappeared from the *Map View* and will also no longer be selectable within the *Attributes table* (there are only 49 features left, Fig. S 85.). However, they are not deleted from the file and can be restored by removing any SQL "where clause" in the *Query Builder*.

For other applications where a section of a vector file should be selected without blanking out all the other features, the same *Query Builder* dialog can be accessed by the *Attribute table > Advanced search*. Of particular use is the combination of different "where clauses", e.g. selecting attributes above or below a certain threshold or containing a given text string.

7.4.3. Manual selection

Sometimes the easiest way to select geometries or entries in the *Attribute table* is by hand, especially for digitizing or editing tasks. To create new selections use the *selection* button  within the *Attributes* toolbar. Clicking on the little black arrow to the right, a drop-down menu opens, containing some more options for the selection using rectangles, polygons, freehand forms, or a radius. To select multiple features or to remove some from a given selection, hold the CTRL key (Windows) down while selecting or deselecting the features with the left mouse button (see the manual (QGIS Development Team, 2013) for the same function on Mac and Linux).

Any selection can be removed using the main menu *View > Select > Deselect Features from All Layers* or the button  within the *Attributes* toolbar.

7.4.4. Creating new layers from selected data







If a given selection has to be exported into a new layer, e.g. to share the file with business colleagues, this can be done by saving a vector layer (see section 7.3.3.): open the layers context menu by a right-click within the *Map Legend > Save Selection As*. Choose all the polygons in the layer *commune_boundary_FR.shp* that intersect with at least one of the honey bee locations with a selection tool of your choice and load the new created layer into the QGIS project (Fig. S 86.).

The newly created polygon layer will only contain 11 features and will again be symbolized by a non-transparent simple fill pattern.


7.4.5. Attribute table data editing

QGIS provides a set of editing tools and conventions similar to ArcGIS (see section 6.4.3.). To edit a vector layer, it has to be set into "edit


Table 6. The most important functions and the corresponding buttons for editing tasks.

Function	Icon	Purpose
Toggle editing mode		Start and End editing sessions. Changes have to be confirmed (or rejected) at the end of an editing session.
Save Edits		Saves the edits permanently.
Delete Selected Features		Deletes only the selected features
New column		Inserts a new column (field) at the end of the attribute table. A field name and a data type must be defined.
Delete column		Deletes the selected column(s)
Open field calculator		Opens the field calculator


mode" by the *Toggle Editing* function. As usual, this function is accessible by several buttons and menu entries:

- Main menu *Layer > Toggle Editing*.
- The button *Toggle Editing*  within the *Digitizing* toolbar or the *Attribute table*.
- The context menu within the *Map Legend > Toggle Editing*.

If the *Toggle Editing* function is greyed out, the selected layer is probably not in an editable vector file format (not all the file formats that can be imported and displayed with QGIS may also be changed, so that in some cases a file conversion is necessary first) or accessed by another program or other users.

1. Set the newly created layer containing all municipalities where colonies of honey bees were sighted into the *Edit mode*.
2. In the *Map Legend* a pencil will appear to the left of the layers name and in the *Map View* the different vertices of the polygons are marked by transparent circles.
3. Open the *Attribute table* and look at the buttons to the left (see Table 6):
4. Now add a new field (column in the *Attribute table*) with the button , where additional values (e.g. the number of honey bee colonies) can be filled in.
5. Within the *Add column* dialog, choose appropriate settings for *name* (avoiding special characters and blanks, e.g. 'bees_colonies'), *data type* (e.g. integer, only whole numbers will be needed) and *width* (2 digits are sufficient as there will not be more than 99 colonies per entry).
6. Now, fill in some numbers into the newly created fields as a test (Fig. S 87).

Because of the restriction to integer values of 2 digits maximum width, all types of characters and also numbers higher than 99 will be refused. This is one of the ways GISystems deal with aspects of data integrity.

7. Click the *Save Edits* button  to make the changes permanent, i.e. written to the file system.

Save often to avoid data loss and finish successful edit sessions by turning the edit mode off (*Toggle Edits* button again > *save all changes*).

The number of honey bee colonies could be counted and written to the table manually, but of course QGIS provides several tools for this task that run automatically, even when the *editing mode* is not active or no empty field has been created before:

1. Go to *Vector*.
2. Choose *Analysis Tools*.
3. Select *Points in Polygon*.
4. Choose the appropriate *input layers* and a *name* for the *new attribute field* (e.g. "bee_colony")
5. Specify a path and a name for the new shapefile that will be created (Fig. S 88).
6. Click *OK*.
7. Click *Yes* when asked if the newly created shapefile should be added to the table of contents (TOC).

In which commune are most honey bee colonies located?

1. Switch back to the *Attribute table* of the new shapefile.
2. Sort the attributes by descending in the field "bee_colony" (click the arrow beside of the column name).

Within the commune of "Düdingen", with the "BFSNR" = 2293, 5 colonies of honey bees were found.

7.4.5.1. Using the field calculator and adding geometry columns

As the communes in this example have different areal extents, one could also ask for the commune area in relation to the number of honey bee colonies. With GIS software, this kind of problem is easy to solve. Also the extraction of statistical information about geometries like *point coordinates*, *line length*, *perimeter* or *area* from the features of a vector layer can be efficiently processed.

Let's demonstrate this with the polygon layer already containing the attribute "bee_colony" created in the previous section:

1. Open the *Attribute table*.
2. Again toggle on the *Edit mode*.
3. Open the *Field calculator*.
4. Activate the checkbox to *create a New field*.
5. Set the *output field name* to something like "area_bee" and the other parameters as follows: *field type* (decimal number), *width* (10) and *precision* (3).

6. Search now for "area" within the *Function List > geometry* and select the function with the name $\$area$ by a double click.
7. Click the appropriate button for a division operation and select the field containing the number of honey bee colonies.
8. Confirm with *OK*, if the resulting *Expression* corresponds to " $\$area / bee_colony$ " (Fig. S 89, "bee_colony" represents the column name, selectable by *Function List > Fields and Values*).

The values in the field "bee_area" (to the right within the *Attribute table*, ratio area per bee colonies) could be a first indicator about the occurrence of honey bees (of course with strong limitations, as the polygon layer only represents administrative boundaries): The minimum value belongs to the community of "Granges-Paccot" with the "BFSNR" 2198.

We learned in this section to calculate the area of a polygon layer and write these values into an *attribute field*. Another possibility to add standard geometry information (e.g. point coordinates, line length, perimeter or area) is the *function Export/Add geometry columns*. This function is of particular use in combination with different coordinate reference systems (CRS), which can easily be demonstrated with the KML file created in section 7.3.3.2. (e.g. bees_colony_locations_WGS84.kml):


1. Go to *Vector*.
2. Select *Geometry Tools* (Fig. S 90).
3. Choose *Export/Add geometry columns*.
4. Select bees_colony_locations_WGS84 as Input vector layer.
5. Choose to calculate the geometry columns using the *Layer CRS* (e.g. WGS84).
6. Specify the *path* and *filename* for the destination file that will contain the geometry columns (it is the best to convert it back to a shapefile again).
7. Click *OK* and wait until the progress bar is at 100%.
8. Confirm to import this new shapefile by clicking *Yes* on the *next* dialog and close the *Export/Add geometry columns* window.
9. Open the *Attribute table* of the new shapefile.

Like its origin (the KML file), the shapefile is referenced in WGS84 but because of the "on-the-fly" CRS transformation, the points representing the honey bee colonies are still congruent with those referenced in the projected coordinate system (which is defined as CH1903 / LV03). Within the *Attribute table* two new fields have been created that show the latitude and longitude in degrees (according to WGS84).

7.4.5.2. Table manager plugin

New attribute fields can be added or deleted directly within the *Attribute table* or the *Field calculator* dialog. But at this stage there is no option to rename any given field. For all changes within the table structure (adding, renaming and removing operations), the *Table manager plugin* is the perfect tool. As this is an optional plugin, it has to be downloaded first from the Official QGIS Repository (see section

7.1.3.). In this example, we rename the geometry columns:

1. Go to *Plugins*.
2. Select *Table*.
3. Select *Table Manager* (the *edit mode* has to be turned off).
4. Locate the *field* in the list called "XCOORD".
5. Click the *Rename* button  and rename it as "longitude".
6. Click *OK*.
7. Do the same with "YCOORD" renaming it as "latitude".
8. Confirm the changes by the button *Save*.

If changes are made for fields used for layer styling or labelling, some features may become invisible. This should not be the case in this example.

9. Click *Yes* to keep the current layer style.

The *Table Manager* is very strict in terms of the length of field names and the characters allowed. Due to this, it may be difficult to find suitable field descriptions, but this is the price to pay for preserving interoperability options between different file formats.

10. Save the layer to a new shapefile into the CRS CH1903/LV03 (see section 7.4.4., e.g. with the name bees_colony_locations_coordinates.shp)
11. Import this new shapefile (e.g. and add geometry columns again, see section 7.4.5.1.)
12. Open its *Attribute table*.
13. Compare the different columns.

Now the coordinates of the points are listed as attributes in the two CRS, one in degrees (WGS84) and one in meters (CH1903/LV03).

7.5. Format conversions and projections

QGIS provides a variety of different conversion functions between vector and raster data formats similar to other GIS software like ArcGIS (sections 2.2 and 6.7.). The most important plugin for data conversion functions within QGIS is called *GDAL Tools*, so make sure it is installed and activated (see section 7.1.3.).

7.5.1. Vector to raster

The *Vector to raster* function rasterizes vector geometries into the band(s) of an existing or a new raster image.

1. Go to *Raster*.
2. Select *Conversion*.
3. Choose *Rasterize (Vector to raster)*.
4. Choose the input shapefile (e.g. the layer commune_boundary_FR.shp) and a suitable *attribute field* (e.g. "Shape_Area").

Be aware that any layer intersection (different features overlaying each other) cannot be transformed to raster data without data loss (in the intersecting areas).

5. Specify an output raster file and a resolution in pixel value (Fig. S 91).
6. Launch the conversion by clicking *OK*.

The newly created raster image will probably be displayed in

uniform grey colour. To apply different colours for the corresponding values (generated by the shape area of each polygon) proceed as follows:

1. Open the *Layer Properties*.
2. Select *Style*.
3. Choose *Single band properties*.
4. Select *Colormap* in the dropdown menu *Color map*.
5. Switch to the tab *Colormap* and increase the number of entries, e.g. to 5.
6. Click *Apply*.
7. Navigate to the tab *Transparency* and make 0 values transparent (otherwise regions outside of the original polygon remain filled).
8. Have a look at the changes on the *Map View* by clicking *Apply*.
9. Close the *Layer Properties* with *OK*, if the result looks similar to Fig. S 92.

Notice that the resolution of the polygon boundaries is coarse in the raster and not as smooth as in the original vector layer (zoom to the boundaries).

7.5.2. Raster to vector

As the name of this function suggests, a polygon layer will be created according to the different raster values (contrary to the function *Contour* demonstrated in section 7.7.2.4., which creates a line vector layer based on raster grid values).

1. Go to *Raster*.
2. Select *Conversion*.
3. Choose *Polygonize (Raster to vector)*.
4. Choose the newly created raster from the previous section (7.5.1.) and convert it back to a vector file (so specify an output shapefile, see Fig. S 93).
5. Start the conversion by clicking *OK*.
6. Open the newly created shapefile.

An attribute field containing the former raster values will be created.

Beside the fact that the geometry became coarser (the boundaries are no longer smooth), we see that many of the original attributes have been lost (e.g. as seen with the *Identify* tool or within the *Attribute table*).

7.5.3. Reproject data to a new coordinate reference system (CRS)

Sometimes, not only one raster file needs to be converted to another coordinate reference system, but a whole folder with many raster images. In this example, the ASTER30_WGS84 DEM will be projected to the CRS CH1903/LV03 of Switzerland.

1. Go to *Raster*.
2. Select *Projections*.
3. Choose *Warp (Reproject)*.

4. Select *single input* and *output* files (e.g. ASTER30_dem_CH1903) or source and destination folders (for processing in batch mode).
5. Specify both the source and *target reference system (SRS)*.
6. Choose *bilinear* or *cubic* as *Resampling method*.
7. Activate the checkbox *Load into canvas when finished* (Fig. S 94).
8. Start the projection by clicking *OK*.

Depending on the type of the raster image values different *Resampling methods* should be used (e.g. nearest neighbour for categorized thematic data and bilinear or cubic for continuous data such as raster images like elevation models). In addition, it might be useful to define a value for pixels without data (so that they can be made transparent afterwards).

7.6. Basic vector tools

The standard tools for data processing and analysis provided by different GIS software have a similar appearance. All tools described in the following sections can be accessed by the main menu *Vector > Geoprocessing Tools* (if the plugin *fTools* has been successfully installed and activated before, see section 7.1.3.).

7.6.1. Buffer(s)

In QGIS, the *Buffer* tool can be accessed in the following way (see section 6.5.5. for a description of the tool):

1. Go to *Vector*.
2. Select *Geoprocessing Tools*.
3. Choose *Buffer*.
4. Select a realistic *buffer value* for honey bees (e.g. 2,000 meters).
5. Leave the *dissolve option* blank (otherwise all buffers will be aggregated to one single feature without the different attributes, see Fig. S 95).
6. Specify the *path* and *name* for the *destination file*.
7. Click *OK*.
8. Click *YES* to confirm loading the newly created vector file to the QGIS project.

One should consider the use of the buffer function may lead to topologically incorrect vector files, e.g. when the distances between the features of origin are closer than the double buffer radius, leading to overlaps between different features. The circle polygons created in this step are visible in Fig. 99.

7.6.2. Clip

See section 6.5.1. for a description of the *Clip* tool. As an example, the clip operation could be performed between the honey bee locations and the commune of Fribourg.

1. Activate the layer *commune_boundary_FR.shp* in the *Map Legend*.
2. First select the polygon that represents the city of Fribourg ("BFSNR" = 2196) with an appropriate selection tool (see section 7.4.).

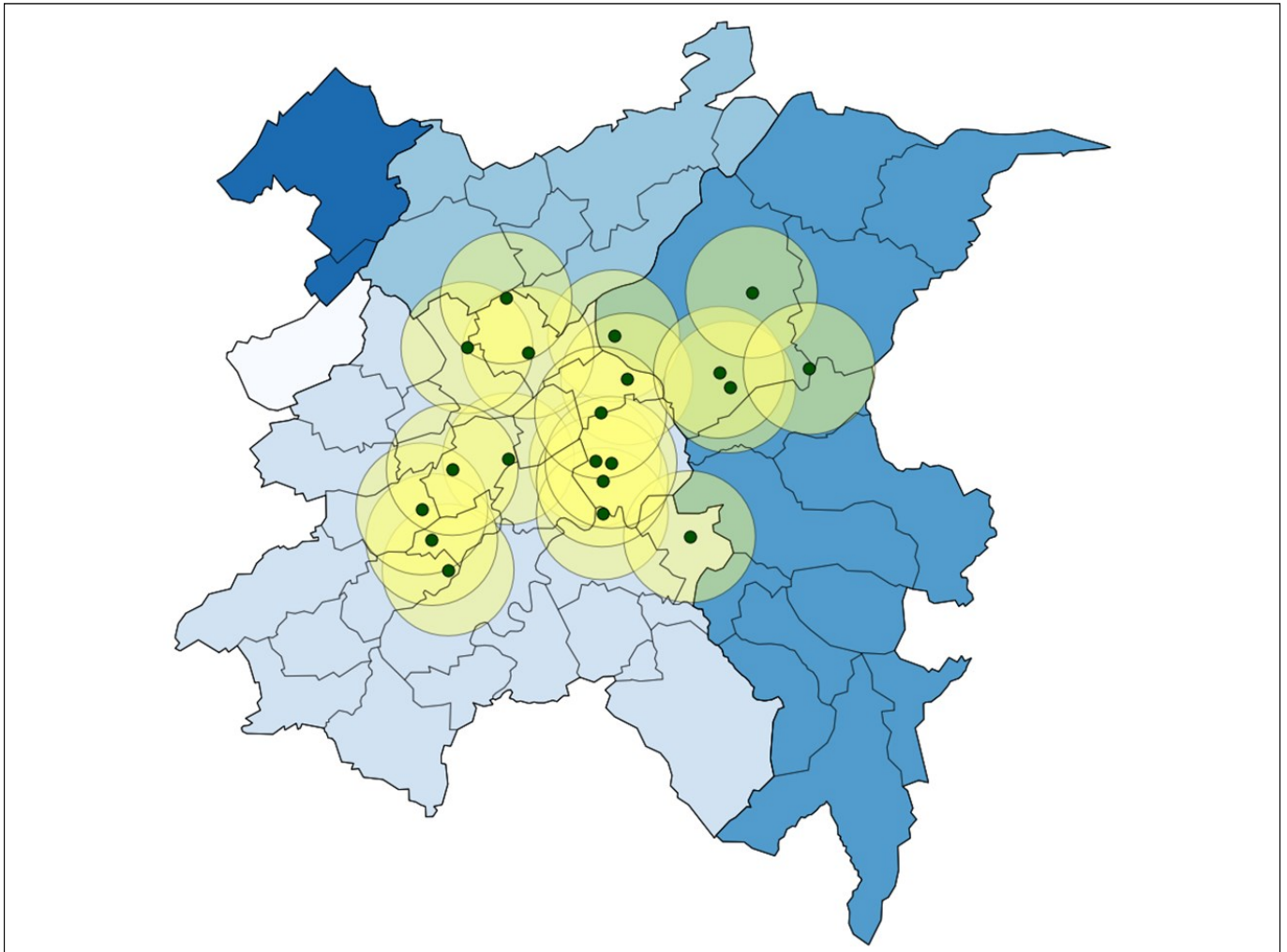


Fig. 99. After applying the Dissolve tool, the polygon layer is divided into 5 different districts. The thin black lines on top represent the former state (51 different municipalities). The yellow circles were created using a radial buffer of 2000 m around of all the honey bee colony locations. Reproduced with permission of Swisstopo (BA13016).

3. Open the Clip tool, go to *Vector*.
 4. Select *Geoprocessing Tools*.
 5. Choose *Clip*.
 6. Choose the point layer containing the honey bee colony locations as *Input vector layer* and the polygon layer as *Clip layer*.
 7. Make sure that the checkbox the Input Vector Layer *Use only selected features* (with this the operation could be performed on a selection of features only) remains blank (there is no selection), and that the one for the *Use only selected features* Clip Layer (beneath) is checked (Fig. S 96).
 8. Launch the Clip operation by clicking *OK*.
 9. Click *YES* to confirm loading the newly created vector layer (containing only 3 points) to the project.
1. Go to *Vector*.
 2. Select *Geoprocessing Tools*.
 3. Choose *Intersect*.
 4. Choose the newly created buffer layer as *Input vector layer*.
 5. Leave the checkbox beneath *Use only selected features* blank.
 6. Select the layer *commune_boundary_FR.shp* (where the city of Fribourg should still be selected).
 7. Check *Use only the selected feature* of this layer of the city of Fribourg (Fig. S 97).
 8. Click *OK*.
- The new layer contains only the common area of the two polygons (the geometry of the buffer within the city of Fribourg).

7.6.4. Dissolve

7.6.3. Intersect

Identically to ArcMap, the intersect operation in QGIS computes a geometric overlap of two layers. This can be best demonstrated by the use of two polygon layers with different geometries:

In section 7.4.2., a definition query was set from the polygon layer representing different municipalities within the canton of Fribourg (Fig. S 85). To aggregate all features that contain the same attribute "KANTONSNR" by producing a vector layer of all districts, the *Dissolve* function is a good option (see section 6.5.7. for further explanation about the dissolve tool):

1. Open the *Query Builder* for the polygon layer you want to use by right-clicking.
2. Make sure that no restriction is made within the SQL "where clause" (If you use the layer *commune_boundary_FR.shp*, delete the entry "KANTONSNR" = 10, if this still exists).
3. Confirm with *OK*.
4. Go to *Vector*.
5. Select *Geoprocessing Tools*.
6. Choose *Dissolve*.
7. Locate the layer *commune_boundary_FR.shp* as *Input vector layer*.
8. Leave the checkbox *Use only selected features* blank (with this the operation could be performed on a selection of features only, but in our case no selection has to be applied).
9. Select an attribute (e.g. "BEZIRKSNR") as *Dissolve field*.
10. Choose a *path* and *name* for the *destination file* to be created (Fig. S 98).
11. Finish by clicking *OK*.

Now the whole canton of Fribourg is selectable at once (representing only one line within the *Attribute table*), and the "island polygons" in the north-western part demonstrate what is meant by a "multipart polygon". What happened to the attributes? – Of course some of the attributes are no longer thematically correct: the dissolve function allocates the attributes from the first line of each value that was aggregated. The display of the new layer can be improved:

12. Open the *Layer Properties*.
13. Select *Style*.
14. Set a categorized symbol style with different fill colours for all 5 districts (by using the column "BEZIRKSNR").
15. Choose a colour ramp.
16. Click *Classify*.
17. Apply the changes.
18. Close the *Layer Properties* dialog by clicking *OK*.
19. The result will look similar to Fig. 99.

7.6.5. Union

In QGIS the *Union* tool can be found within *Vector > Geoprocessing Tools > Union* (see section 6.5.3. for an explanation of the *union* function).

7.6.6. Join attributes by location

In section 7.4.1. spatial queries were performed. In a similar manner, different layers and their features can also be spatially linked to each other, e.g. to relate thematic data to known coordinates or geometries:

1. Go to *Vector*.
2. Select *Data Management Tools*.
3. Choose *Join attributes by location*.

4. Select a *target* (e.g. *bee_colony_locations.shp*) and a *join vector layer* (where the attributes are taken from, e.g. *commune_boundary_FR.shp*).
5. Choose how the attributes should be attached to the target layer (by the first matching feature is usually the best choice if text fields are joined, but in the case of numerical attributes different aggregation modes may also be suitable).
6. Set the *path* and *name* for the destination shapefile (Fig. S 100).
7. Click *OK*
8. Load the new shapefile into the project by clicking *Layer > Add Vector Layer*.

Within the *Attribute table* of the new shapefile, the attributes of the commune layer will be added.

7.6.7. Basic statistics, list unique values

Especially for large vector data files containing a variety of attribute fields and features, it can be useful to display some statistical information before performing calculations with these attribute values. Two very useful tools are provided by the *fTools plugin* (see section 7.1.3.) and explained in the following examples:

To display basic statistics based on attributes,

1. Go to *Vector*.
2. Select *Analysis Tools*.
3. Choose *Basic statistics*.
4. Any vector layer can be chosen within the QGIS project as *Input Vector Layer*.
5. Select a *target field*, where the statistics (mean value, standard deviation, sum, minimum, maximum etc.) should be performed.
6. Click *OK* (Fig. S 101).

Sometimes the total number of attribute values within a given field are not important, but the different values themselves are:

1. Go to *Vector*.
2. Choose *Analysis Tools*.
3. Select *List unique values*.
4. Select a *target vector layer* and an *attribute field*.
5. Click *OK* to perform the calculation.

It is possible to export the values to the clipboard if they are used in another program (e.g. calculation spread sheet or text editor).

7.7. Basic raster tools

In the following section, some basic raster functionalities in QGIS will be discussed. Many of these tools rely on the *GDAL Tools plugin* (see section 7.1.3.), so install or activate this first.

7.7.1. Merge

The *Merge* function is similar to the mosaic tool of ArcMap, where several raster layers and files can be combined to a new raster dataset (see section 6.6.1. for more information).

1. Go to *Raster*.
2. Select *Miscellaneous*.
3. Choose *Merge*.
4. Select the *input raster images* (or even a whole *directory*).
5. Create one single *output raster file* in a *destination folder*.
6. Enable the lowermost checkbox so that the new raster image will be added directly to the project.

7.7.2. Terrain analysis

Beneath the elevation information itself, DEMs can serve as a source of data for various terrain analysis operations to calculate geometrical properties (e.g. slope or aspect) and other derivatives (e.g. clear sky factor). All functions for terrain analysis are accessible by the menu *Raster > Terrain analysis*. In some cases these functions are also useful for analysis or visualisation of thematic raster data.

7.7.2.1. Slope

The *Slope (Terrain analysis)* tool calculates the slope angle of each raster cell in degrees.

To calculate the slope of the terrain (Fig. S 102):

1. Go to *Raster*.
2. Select *Terrain analysis*.
3. Choose *Slope*.
4. Choose the DEM as the *input raster*.
5. Browse for a destination path and save the *output raster* as "slope".
6. Choose the *output format* to be used from the list (various formats within GDAL).
7. Click *OK*.
8. Adapt the raster symbolization if necessary (*Layer Properties > Symbol*).

Besides the *Terrain analysis* tools there is a set of *Terrain analysis* functions (with even more options) provided by the *GDALTools Plugin* (Fig. S 103): these tools are accessible by menu *Raster > Analysis > DEM (Terrain models)*.

7.7.2.2. Aspect

The *Aspect (Terrain analysis)* tool uses a DEM to calculate the direction in which slopes are facing (see section 6.6.2.2. for more information).

To calculate the aspect based on a DEM:

1. Go to *Raster*.
2. Select *Analysis*.
3. Choose *DEM (Terrain models)*.
4. Choose the mode *Aspect* (Fig. S 103) (the function *Raster > Terrain analysis > Aspect* is just another option to achieve the same result).
5. Select the DEM as the *input raster*.
6. Browse for a destination path to save the *output raster* as *ASTER30_aspect_CH1903.tif*.

7. Some *optional settings* can be activated or deactivated in the checkboxes, to make flat areas (that do not have a valid aspect value by default) zero values, for instance.
8. Click *OK*.
9. Adapt the raster symbolization if necessary (*Layer Properties > Symbol*).

7.7.2.3. Hillshade

Hillshade rasters are useful for determining which areas on the terrain are shaded from the sun and which are not and are calculated from a DEM (see section 6.6.2.3) for further information about the tool.

To calculate the hillshade based on a DEM:

1. Go to *Raster*.
2. Select *Terrain analysis*.
3. Choose *Hillshade*.
4. Select the DEM as the *input raster*.
5. Specify an *output (raster) layer*.
6. Choose reasonable values for the horizontal and vertical angle of the illumination (in degrees), the Z factor can usually stay at 1 (otherwise the terrain will be super-elevated when working in a CRS).
7. Click *OK*.
8. Adapt the raster symbolization if necessary (*Layer Properties > Symbol*, notice that the results are shown in degrees (Fig. S 104)).

7.7.2.4. Contour

This function generates an output vector file containing elevation levels (contour lines) from an input raster (see section 6.6.2.4. for more information). To create contours from a DEM:

1. Go to *Raster*.
2. Select *Extraction*.
3. Choose *Contour*.
4. Specify the *input DEM* and the *output vector file*.
5. Choose an appropriate interval between the different contours (e.g. 50 meters).
6. Activate the first checkbox to store the elevation information within an *attribute* and specify a *field name* (Fig. S 105).
7. Click *OK*.
8. Load the resulting vector layer into QGIS.

To achieve better results for visualisation, a smoothing algorithm could be performed on the line feature, e.g. with the tool *Simplify geometries (Vector > Geometry Tools > Simplify geometries)* or the *Generalizer plugin (Plugins > Generalizer > Generalizer)*.

Contour lines can also be created by the *Contour plugin* that provides some more options (e.g. minimal and maximal height). After the installation (see section 7.1.3.) it can be started in the menu *Plugins > Contour > Contour*.

7.7.3. Raster calculator

The raster calculator is a very flexible and useful tool to combine raster images with conditional and trigonometric expressions and any other task that requires raster math operations. It can be found within the menu *Raster > Raster calculator*. The formula "ASTER30_dem_CH1903@1 * 3.28084" would convert the elevation data in the DEM from meters into feet by creating a new raster image (with an elevation range from 1,332 to 2,982 feet).

7.8. Spatial statistics and scientific modelling

QGIS provides several tools for spatial statistics and interfaces to statistical software like R (<http://www.r-project.org>). This section demonstrates some introductory examples of how statistics of spatially related data can be processed, as well as suggestions for useful plugins and software to perform more sophisticated spatial analysis. If you search for a specific application linked to spatial statistics, browse through the *QGIS Plugins* (see section 7.1.3.) and have also a look at the projects and their features listed on the OSGEO website (<http://www.osgeo.org>). A more general introduction to statistics in honey bee research is provided in the *BEEBOOK* paper on statistics (Pirk *et al.*, 2013).

7.8.1. Example 1: Computing mean coordinates

A very basic analysis could be to compute the mean coordinates of the honey bee locations. Of course this could be done by computing the X and Y coordinates into an attribute first, but now we will use the tool mean coordinate(s):

1. Go to *Vector*.
2. Select *Analysis Tools*.
3. Choose *Mean coordinate(s)*.
4. Select the *input vector layer* (e.g. bees_colony_locations.shp).
5. Specify the *output shapefile* (Fig. S 106).
6. Start the calculation with *OK*.

The new shapefile will contain one point at the coordinates 577289.7 / 184622.7.

7.8.2. Example 2: Nearest Neighbour Analysis and Distance matrix

Is the spatial distribution of our honey bee colonies disperse or clustered? – The level of clustering in a point vector layer can be assessed by *Nearest Neighbour Statistics (Analysis tools)*:

1. Go to *Vector*.
2. Select *Analysis Tools*.
3. Choose *Nearest Neighbour Analysis*.
4. Select the *point vector layer* representing the bee's locations.
5. Click *OK* to view the result.

In this case, the observed mean distance between nearest neighbours is 1356 meters. If the distances between different points (or groups of points) are of interest, the *Distance matrix* function can be useful:

1. Go to *Vector*.
2. Select *Analysis Tools*.
3. Choose *Distance Matrix*.
4. Select the bees_colony_locations.shp as both *input* and *target vector layer*.
5. Select the field ID as *unique field* (Fig. S 107).

This function could also be performed using two different point layers, or using the same layer but different ID fields.

6. Click *OK* to perform the calculation and view the result.

The resulting delimited text file contains a list of all point combinations and the distance (computed in map units, thus meters in our example) in-between these points. In case of our honey bee locations, the maximal distance (12.5 kilometres) is between the honey bee colony Nr. 12 and 20, the minimal distance is only 484.5 meters (between ID 1 and 16).

7.8.3. Example 3: Computing intersections between a DEM and planes

GIS is very useful for applications in natural sciences and a variety of tools are provided, e.g. for visibility analysis or to delimit watersheds, calculate flow paths, or even simulate natural hazards. This example demonstrates a very specific function, based on the *qgSurf plugin* for QGIS:

1. Load and activate the *plugin qgSurf* (see section 7.1.3.).
2. Go to *Plugins*.
3. Select *qgSurf*.
4. Select the DEM ASTER30_dem_CH1903 and choose *source point* for the plane (e.g. around Fribourg 578000/183000/627).
5. Play around with the values for *orientation* and *inclination* of the plane and *calculate the intersections* (Fig. S 108).
6. Save the output as point or line shapefile.

To analyse spatially related processes in more detail or for modelling, functions within GRASS GIS (<http://grass.osgeo.org>, Neteler and Mitasova, 2008) or SAGA (<http://www.saga-gis.org>) can be useful. To access these, GRASS and/or SAGA have to be installed on your computer and within QGIS the *SEXTANTE Toolbox plugin* (<http://plugins.qgis.org/plugins/sextante>) needs to be installed and configured correctly (see QGIS Development Team, 2013). If you work with R, the plugin *Spatial Data Analysis for Point Pattern (SDA4PP)* might also be a good option (see section 7.1.3.).

7.9. Case study – zonal statistics with land cover properties

Until now, several concepts and tools in QGIS have been introduced. Now, to combine some of the different tasks discussed, a case study will be presented. Within this short case study, geostatistical relationships between honey bee colonies and land cover properties will be calculated. The content of this case study is equal to the one for ArcGIS (see section 6.9.), but adapted to the tools of QGIS. The

prerequisites for this case study include an opened QGIS project (see sections 7.3.1. and 7.3.3.) with a point vector layer (e.g. the honey bee colony locations `bees_colony_locations.shp`, created in section 7.3.3.1.) and a buffer polygon layer (e.g. `bees_colony_locations_buffer.shp`, created in section 7.6.1.). For more information about this case study see section 6.9.

7.9.1. Downloading and extracting

First we need land cover information for the region around Fribourg. If you have already downloaded the CLC06 dataset for the ArcGIS case study (see section 6.9.), skip the following paragraph and continue with step 4.

1. Download the dataset `g100_06.zip` (CLC06 – 100 m) from the website <http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2> to a local directory (e.g. on the Desktop).
2. Unzip the file `g100_06.zip` with a file archiving program of your choice (if you need additional software for this task, the program "7-zip" is a good choice: www.7-zip.org) into your QGIS working directory (e.g. "BeeBook_data").
3. Navigate to the raster `g100_06.tif` in QGIS Browser to open the tab *Metadata*. For a first visual impression of the data, you can also check out the *Preview* tab.

From step 3 you see that CLC06 is a 1 band raster dataset with 8 bit unsigned integer values (that correspond to different land cover categories) at 100 m horizontal resolution. Because it covers all Europe, the CLC06 raster is quite big and the rendering on the screen may take some time. We will improve the performance by clipping on the extent of interest (see steps 15-22).

7.9.2. Projecting data into another coordinate reference system (CRS)

The coordinate system is different (ETRS89 / ETRS-LAEA, EPSG-code 3035) from that one of Switzerland, and for our purpose its best to bring it into the same coordinate reference system as the other layers (CH1903 / LV03).

4. Switch to QGIS Desktop.
5. Open the menu *Raster*.
6. Choose *Projections*.
7. Click *Warp (Reproject)*.
8. Select the raster image `g100_06.tif` as *Input file*.
9. Choose a name and destination for the *Output file* (e.g. `g100_06_ch1903.tif`).
10. The Source SRS should be automatically detected (ETRS89 / ETRS-LAEA), but the *Target SRS* has to be defined: click *Select >* filter for "CH1903 / LV03" and select the remaining CRS listed.
11. Confirm with *OK*. The EPSG-codes should be set corresponding to Fig. S 109.

12. Choose the Resampling method *Near* because we have categorized data and want to keep the original integer values (see section 7.5.3.).
13. Activate the checkbox *Load into canvas when finished*.
14. Click *OK*. The projection process of large raster datasets can take several minutes depending on the computer processing power, so please be patient.


7.9.3. Clipping to study area extent

The resulting raster `g100_06_ch1903.tif` still covers all Europe, so we will now clip it to the extent of our polygon layer `commune_boundary_FR.shp`.


15. Open *Raster*.
16. Select *Extraction*.
17. Open *Clipper*.
18. Select `g100_06_ch1903.tif` as *Input file*.
19. Choose `CLC06_Fribourg.tif` as *Output file* name.
20. Choose *Extent* within the *Clipping mode* and enter the minimum and maximum values for x and y according to Fig. S 110 (xMin: 564835, yMin:168930, xMax: 593200, yMax: 196915). To look up these values, double-click the layer `commune_boundary_FR.shp` in the *Map Legend > Layer Properties > Metadata*. In GIS, minimum and maximum x and y values can also be obtained manually by hovering over a location on the map and reading the x and y values from the bottom right-hand corner of the screen (Fig. S 110).
21. Activate the checkbox *Load into canvas when finished*.
22. Click *OK* to start the clipping process.
23. After the clipping has finished, remove the big layer `g100_06_ch1903.tif` from the *Map Legend*.
24. The result should then look similar to Fig. S 111.

7.9.4. Raster layer styling and predefined colour maps

The layer `CLC06_Fribourg.tif` is now quite handy for our purpose, but so far we do not know for what the numbers (raster values) stand for (see Fig. S 111). Luckily, a colour map is provided by the European Environment Agency (EEA) and can be loaded into QGIS (similar to the ArcGIS layer file, see section 6.9.4. for more information):

25. Double-click on the layer `CLC06_Fribourg` in the *Map Legend* to open its *Layer Properties*.
26. Navigate to the Tab *Colormap* and Click the Symbol  *Load color map from file*.
27. Navigate to the folder that you have unzipped in step 2 (e.g. `CORINE_2006_100m`), select the text file `clc_legend_qgis.txt` and *click Open*.
28. Click *Apply* (see Fig. S 112) and close the Layer Properties with *OK*.

Note that the raster values do not correspond with the numbers (categories) indicated in the labels (Fig. S 112). You can verify this by

using the *Identify Features* button  and comparing this with the entries in the Map Legend. This might be a little confusing, but the reason is of technical nature: the official CLC06 land cover category numbers (50 in total) ranging from 111 to 999 cannot be displayed with a single band 8-bit integer raster dataset, where the range of raster values is limited to 0-255. Of course a 32-bit floating-point raster image could be used to display the whole range from 111 to 999, but then the dataset would become almost 4 times larger and unhandy for download, storage and analysis. In the following tasks we will make use of numbers written in the labels of CLC06_Fribourg.tif.

7.9.5. Conditional expressions using the raster calculator

Let's now analyse the area covered by some land use types of interest (arable land, forests) within the buffer zones of our honey bee colonies (see section 6.9.6. for more information).

29. Open the menu *Raster > Raster calculator*.
30. Combine *Raster bands* and *Operators* until the *Raster calculator expression* equals "CLC06_Fribourg@12 = 211" (211 is the raster value for "non-irrigated arable land in the CLC06 dataset).
31. Specify an *Output layer*, e.g. CLC06_class211.tif.
32. Activate the Raster band CLC06_Fribourg@1 again and click *Current layer extent* to make sure that the output layer has the same extent as the source.
33. Verify that the parameters are set according to Fig. S 113 and click *OK* to start the calculation.
34. Double-click on the new greyscale Layer CLC06_class211 to open the *Layer Properties > Tab Style*.
35. Check *Estimate (faster)* within *Load min/max values from band* and click *Load*, select *Stretch to MinMax in the Contrast enhancement* (see section 7.3.3.).
36. Click *Apply* to make the layer styling effective and close the *Layer Properties* dialog with *OK*.
37. Repeat steps 29 to 36 with the following raster values: 24 (class 312, Coniferous forest) and 25 (class 313, Mixed forest).

7.9.6. Zonal statistics of land cover values within buffers

The newly created raster images contain zones with the value 1 (where the *Raster calculator expression* was true) and 0, where the expression was false. This binary classification can now be used to calculate the percentage of each land cover class within any polygon layer, e.g. the honey bee colony buffers (also see section 6.9.7.):

38. Open the menu *Raster > Zonal statistics > Zonal statistics*.
39. Choose one of the newly created binary raster images (e.g. CLC06_class211.tif) as input *Raster layer*.
40. Select bees_colony_locations_buffer.shp as input Polygon layer containing the zones.

41. Choose an appropriate column prefix (e.g. the land cover class "211") and Click *OK*.
42. Repeat steps 38 to 41 for the other input rasters (choosing appropriate filenames for the results, see Fig. S 114).

Opening the attribute table of the layer bees_colony_locations_buffer.shp, you see new fields at the end: The field "211mean" represents the average percentage of the land cover category "non-irrigated arable land" within the respective buffer (honey bee colony).




7.9.7. Visualisation of attribute values

The proportion of the three land cover categories can be used for any symbolisation and vector calculation, but also visualized within a simple chart:

43. Open *Plugins > Chart Maker > Chart Maker*. If you don't see this entry, you probably have to install or enable first the *Chart Maker plugin* (see section 7.1.3.).
44. Select the *Vector layer* bees_colony_locations_buffer.shp.
45. Set the *attribute fields* for the X and Y axis you want to display (e.g. the ID for X and a land cover percentage for Y).
46. Click *Plot chart* and look at your chart.
47. Feel free to display all land cover categories you have processed by incrementing the *number of series* (see Fig. S 115).
48. If you want, you can save the chart as picture file.

7.9.8. Mathematical operations using the field calculator


Within most of the honey bee colony buffers there are also other land cover categories that can be calculated using the following procedure:

49. Right-click on bees_colony_locations_buffer.shp in the *Map Legend > Open Attribute Table*.
50. Toggle on the *editing mode* with the button .
51. Open the *Field calculator* .
52. Make sure the checkbox *Create a new field* is activated and specify an *Output field name* (e.g. "other").
53. Change the *Output field type* to *decimal*.
54. Increase the *Precision* to 3.
55. Combine the *Attribute Fields and Values* and different operators so that the resulting *Expression* equals $1 - ("211mean" + "312mean" + "313mean")$ (see Fig. S 116.).
56. Click *OK* to perform the calculation and have a look at the new field created on the right within the attribute table..
57. Repeat steps 51 to 56 and add a new *field (type decimal)* called "sum" that summarizes all 3 land use categories 211, 312 and 313 (the *Expression* should equal $211mean" + "312mean" + "313mean"$).
58. Toggle off the *editing mode* with the button .

The resulting attribute field "other" represents the remaining area not covered by the CLC06 categories 211,312, and 313 relative to the total area of the polygon layer. The field "sum" summarizes the relative area covered by these three land cover categories of interest.

7.9.9. Joining attributes from other vector layers

For visualisation purposes (see map creation in section 7.10.) we must join the land cover percentage per honey bee colony buffer (see sections 7.9.6. and 7.9.8.) to the original point layer bees_colony_locations.shp (see 6.9.8. for more information). To do this:

59. Double-click on bees_colony_locations.shp in the *Map Legend* to open its *Layer Properties*.
60. Switch to the *Tab Joins*.
61. Click the button  to *add a join to another vector layer*.
62. Select bees_colony_locations_buffer.shp as *Join layer* (Fig. S 177).
63. Make sure the *Join and Target fields* are set to their identifier "ID".
64. Leave unchecked both of the checkboxes and click *OK*.
65. Click *OK* to close the *Layer Properties*.

Congratulations, you have finished your first geo-statistical analysis with QGIS. The next section is about the creation of maps.

7.10. Map creation

Creating maps with QGIS is similar to the procedure with other GIS software like ArcMap. This section collects the most important steps from managing geographic data to its visualisation (see section 2.3.3.) and requires the results of the case study (see section 7.9.).


7.10.1. Layer styling and labelling

Some basic settings in the *Layer Properties* for styling were already discussed in this tutorial (see sections 7.3.4. and 7.3.5.). Based on this experience, we will look at some more techniques to visualise different geometry types and attribute information together:

1. Add the vector layer commune_boundary_FR.shp to the *QGIS project* (see section 7.3.3.).
2. Double-click this layer in the *Map Legend* to open the *Layer properties*.
3. Select *Style*.
4. Select *Graduated* instead of *Single Symbol*.
5. Choose an *attribute* (e.g. "Shape_Area").
6. Choose a number of *Classes* (e.g. 7) and the *Mode Natural Breaks (Jenks)*.
7. Choose colour ramp (e.g. "BuPu").
8. Click *Classify*.
9. Click *Apply* (the *Layer Properties* can stay open).

As an intermediate result, all polygons (representing different municipalities) are filled with a colour from the chosen spectrum corresponding to the chosen attribute (e.g. "Shape_Area"). This is already a good start, but perhaps the map should also provide the names of the communes?

10. Switch to the *Label* tab (Fig. S 118).
11. Activate the *checkbox* to display labels.
12. Choose an *attribute field* that should be displayed (e.g. "GEMNAME").

13. Feel free to adjust font size and colour or the placement options below.
14. Click *OK*.
15. Activate and select the layer bees_colony_locations_buffer.shp created in section 7.6.1.
16. Place it at least one level higher than commune_boundary_FR.shp.
17. Open again the *Layer Properties*.
18. Select the *Style* tab.
19. Click the button *Change*.
20. Choose *Outline: Simple line* as *Symbol layer type*.
21. Select a dark *colour* (e.g. black), a *Pen width* of about 0.25 and *Dot Line* as *Pen style*. Confirm with *OK*.
22. Set the *transparency* to about 30%.
23. Close the *Layer Properties* of bees_colony_locations_buffer.shp.
24. Move the layer bees_colony_locations.shp on top of the *Map Legend* and open its *Layer Properties*.
25. Not only do colours and attributes matter for the visualisation of spatial data, but also size. To demonstrate this, select the size 5, click *Advanced > Size scale field* and choose an *attribute field* of your choice (e.g. "sum").
26. Adjust the *Size* to reach a good result on the *Map View*. The honey bee colonies close to the city of Fribourg have now the smallest symbols, the ones closer to arable land and forests are bigger.
27. Switch to tab *Diagrams* (Fig. S 119).
28. Activate the checkbox *Display diagrams* and choose *Pie chart* as *Diagram type*.
29. Set the *Size* to about 8 mm, the *Placement AroundPoint* with a *Distance* of 6.
30. Now add some content for the pie charts: Use the Button to add the *fields 211mean, 312mean, 313mean* and *other*  (see section 7.9.). The colours can be adjusted by double-clicking on the coloured bar.
31. Make the changes permanent by clicking *Apply* and close the *Layer Properties* with *OK*.
32. Save the QGIS project (and all the layer styling you have done so far) by the menu *File > Save*.

The result (Fig. S 120) is already a good start for a first visualization of geodata and it will serve as an example for the next paragraphs describing map creation functions.




In some cases it makes sense to save the layer symbology not only within a project, but also for different layers. This can be done layer by layer at the bottom of the *Layer Properties* dialog (see Fig. S 118) using the button *Save Style*. This will safeguard all styling information in a *.qml-file. You can import these styles later also into other projects and apply the styles to more layers (*Layer Properties > Load Style*) – so this is probably the most important time-saver for larger mapping projects within QGIS.

7.10.2. Print composer

The *Print Composer* is the main mapping program within QGIS, equivalent to the layout view of ArcMap (see section 6.10.1.).

1. Click *File*.
2. Select *New Print Composer* and a new window opens.
3. Select *Layout*.
4. Choose *Add Map* in the menu on top.
5. Draw a rectangle to the map canvas below to define the map position.

Within the *Item Properties* to the right you can now see the dimensions and the scale of your map. To get familiar with the *Print Composer* (Fig. S 121), look at all the buttons on top and try to:

- Move or change the map extent using the *Select/Move Item* button 
- Move the map content within the frame with the *Move Item* button 
- Save the current *map as template* using the button 

A map like this may be suitable for certain tasks, but it is not complete. In the next section, it will be shown how additional map elements can be added.

7.10.3. North arrow, scale bar, legend, title, labels

The final map should provide information about the map scale and orientation and explain the map content. Let's now add the most common map elements using the *QGIS Print Composer*:

1. Open the menu *Layout*.
2. Choose *Add Image* and click somewhere on the map canvas (all items can be moved afterwards).
3. Select a north arrow of your choice (within the set of preloaded images).
4. Now add a scale bar (*Layout > Add Scalebar*) and click somewhere on the map. A basic scale bar will show up and within the *Item Properties* the unit label must be defined (e.g. m or meters). There are a lot of other optional settings.
5. Up to now we have no information about the different map elements shown, so we add a map legend. Go to *Layout*.
6. Select *Add Legend*, click somewhere on the map canvas and customize the items listed.
7. The names of the different layers can be changed in QGIS desktop by a right click to the *Map Legend*.
8. Select *Rename*.
9. A map needs a title, or sometimes additional labels to explain some features. Go to *Layout*.
10. Click *Add Label* and place it on top of the map. Labels and legend items can be formatted and changed within the *Item Properties*.
11. Last but not least, try to also add a grid according to the CRS used (in this case it is metric, CH1903/LV03). Click with the *Item selection tool* on the map frame and locate within the *Item Properties* the section *Grid*.

12. Activate the checkbox and experiment with the settings below. At the end, the map should look somehow similar to Fig. S 122.
13. Save the template again, and be proud of your first map made with QGIS!

7.10.4. Exporting a map

Maps can be exported from the QGIS Print Composer in different ways:

- In most cases the aim will be to create a printable PDF file. Go to *File* and select *Export as PDF*. By default the settings should be already in the range for good printing results.
- For special map dimensions or to change the resolution settings, go to the *Composition* tab beside the *Item Properties*.
- Of course a map can also directly be sent to a printer device (*File > Print*).
- For a special purpose it might make sense to export a map to a vector or raster image. The two corresponding functions are *File > Export as SVG* and *File > Export as Image*, respectively.

7.10.5. Cloud mapping and sharing maps online

By the means of the QGIS *Cloud plugin* (see section 7.1.3. and Table 4) developed by Sourcepole (<http://www.qgiscloud.com>), users can easily publish their own maps directly from QGIS desktop to a PostGIS 2.0 database within a cloud online storage. There are also many other ways to share geodata and maps produced by open source GIS using Web Map (WMS) and Feature Services (WFS), for example by the means of the open source projects OpenLayers, MapServer or degree. The official website of the Open Source Geospatial Foundation (OSGeo, <http://www.osgeo.org>) provides a good overview about the different projects and their technical capabilities.

8. Future perspectives

The main purpose of the paper was to stimulate spatial thinking in honey bee research by introducing the basic principles and methods of GIS. With an introduction to the basics of GIS, we hope that more honey bee researchers will build on techniques already developed in the native bee domain, and discover new geospatial methods for exploring the relationships between honey bees and their environment. As of now, relatively few honey bee researchers have studied the effects of how environmental characteristics and mechanisms have affected honey bee health, abundance, and honey production (Berardinelli and Vedova, 2004; Naug, 2009; Henry *et al.*, 2012). Because of the recent colony losses in many parts of the world (Carreck and Neumann, 2010; Williams *et al.*, 2010), it is important to mechanistically study and attempt to discover new factors which directly and indirectly affect honey bee populations (Naug, 2009) from both broad and local scales.

GIS and spatial analyses have been used to make great progress in regards to studying the effects of landscape characteristics in research about native bees (Arthur *et al.*, 2010; Biesmeijer *et al.*, 2006; Chifflet *et al.*, 2011; Choi *et al.*, 2012; Fitzpatrick *et al.*, 2007; Giannini *et al.*, 2012; Kremen, 2002; Kremen *et al.*, 2004; Watson *et al.*, 2011; Williams *et al.*, 2012). Various researchers have looked at the links between land cover properties and their effects on bees using satellite imagery to perform land cover classifications (Arthur *et al.*, 2010; Kremen *et al.*, 2004) and aerial imagery to quantify land cover properties (Watson *et al.*, 2011) using GIS. Positive correlations were established between native bees and their surrounding landscapes, perhaps most notably the link between wooded areas and the increase in bee populations and abundance. In terms of climate, Giannini *et al.* (2012) have used GIS to help reveal that native bees populations are decreasing because of a changing climate and are projected to continue to decline in the future due to the loss of suitable habitats.

Because of the obvious similarities between native bees and honey bees, it is assumed that similar relationships will be found between honey bees and their surrounding landscapes and changing climate. Naug (2009) was one of the first to use GIS to test the effects of land cover changes on honey bee colony health and productivity. By looking at the effects of nutritional stress due to habitat loss in the U.S.A., Naug (2009) established that the relative extent of open land area is an important predictor of colony losses, and that states with the largest open area proportions had higher honey yields, meaning that their honey bees were more productive. It is necessary to study these types of relationships from a broad scale in order to get a better general understanding of the overall processes linking honey bees to the surrounding environments. Research of this type can and should be expanded upon to explore more specific geographic regions as well as local scales. Climate research, similar to the work by Giannini *et al.* (2012), can also be conducted in GIS to study not only its effects on honey bees directly, but how changes in climate affect honey bee pathogens.

In conclusion, there are numerous opportunities for expanding geospatial analyses in the honey bee domain and we hope that this paper will motivate and stimulate spatial thinking for researchers.

9. Acknowledgements

We would like to acknowledge the Swiss National Science Foundation (SNF) for providing funds to the authors and Swisstopo for the use of their data through a contract with the University of Fribourg for research purposes. We would like to thank Geoffrey Williams, Jamie Ellis, and Vincent Dietemann for suggesting the idea for this paper, and Christina Zweifel for stepping into the world of GIS to test the tutorials. The COLOSS (Prevention of honey bee COlony LOSSes) network aims to explain and prevent massive honey bee colony losses. It was funded through the COST Action FA0803. COST (European Cooperation in Science and Technology) is a unique means

for European researchers to jointly develop their own ideas and new initiatives across all scientific disciplines through trans-European networking of nationally funded research activities. Based on a pan-European intergovernmental framework for cooperation in science and technology, COST has contributed since its creation more than 40 years ago to closing the gap between science, policy makers and society throughout Europe and beyond. COST is supported by the EU Seventh Framework Programme for research, technological development and demonstration activities (*Official Journal L 412, 30 December 2006*). The European Science Foundation as implementing agent of COST provides the COST Office through an EC Grant Agreement. The Council of the European Union provides the COST Secretariat. The COLOSS network is now supported by the Ricola Foundation - Nature & Culture.

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