

Supplementary material

Implementing Green Infrastructure for the spatial planning of peri-urban areas in Geneva, Switzerland

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Table S1. Input raster data for ecosystem services.

Pillar	Category	Service Name	Indicator	Unit	Methodology	Tools	Formula Source
ECOSYSTEM SERVICE	PROVISIONING	potential pharmaceutical components	abundance of medicinal species	number of species	species diversity in a 200m radius on flora species observation (after 1998)	ArcGIS point statistics tool	[1]
		invasive species and pest control	habitats not colonized by invasive species	index	index between 0 (colonized at least by 28 invasive species) and 28 (not colonized at all), representing intersection between flora observations and natural habitat.	ArcGIS analysis	
		microclimate regulation (urban temperature regulation)	shading by trees	shaded surface (ha)	shaded surface represented by the canopy cover proportion by polygon.	Use of lidar to estimate a surface model of tree canopy	
	REGULATING	air quality regulation	fine particles filtered by vegetation	leaf area surface (ha)	$LAI = 0.57 * e^{(2.33 * NDVI)}$. Leaf Area Index based on a mean NDVI (obtained from sentinel data compilation)	Sentinel-2 images (cloudiness) April–October from 2015 to 2018	
		pollination	capacity of ecosystems to sustain insect pollinators activity	pollinator abundance index	uses estimates of the availability of nest sites and floral resources within bee flight ranges to derive an index of the abundance of bees nesting on each cell on a landscape.	InVEST pollination model	
		erosion control	natural elements limiting erosion	sediment retention t/ha/an	InVEST Sediment Delivery Ratio (SDR) model map overland sediment generation and delivery to the stream based on DEM.	InVEST SDR Model	
		landslide protection	permanent protective forest (silvaprotect)	area in ha	Swiss federal data on forest that protect from landslide, mudslides, falling rocks and avalanches.	Existing data	
		flood protection	green areas in areas exposed to flooding	area in ha	Combination of renatured areas near watercourse that are floodable and protect human activity.	ArcGIS analysis	

SUPPORTING	water quality	nutrient retention (phosphorus)	t/ha/an	InVEST Nutrient Delivery Ratio (SDR) model map nutrient sources from watersheds and their transport to the stream.	InVEST NDR Model	
	soil formation	artificiality of soil	index	<i>Artificiality index = log10 pervious / -log10 impervious.</i> Pervious and impervious are 2 rasters based on the habitat map calculated by focal statistics in a 56m radius.	Focal statistics tool in ArcGIS	
	climate regulation through CO2 sequestration	CO2 captured by trees	ton	Geneva canton extrapolation of tree CO2 stock based on a 56,000-tree sample.	i-Tree ECO analysis	
	climate regulation through CO2 sequestration	CO2 sequestered in soils	index	The InVEST Carbon Storage and Sequestration model aggregates the amount of carbon stored in soil according to land use maps.	InVEST Carbon Storage and Sequestration model	
	nature-based recreation and education	accessibility of green areas	path density index	Using soft mobility path data (Hiking, biking, street with sidewalk, horse riding) to measure a path density index (a no data value is then given to each path).	Kernel density tool in ArcGIS	
	habitat connectivity	corridors for deer	index	Measuring landscape connectivity index based on habitat resistance.	Circuitscape	
	habitat connectivity	habitat fragmentation	index	MESH size index that illustrates how much a habitat is fragmented.	Fragstats	[2]
	habitat quality	naturality	index	<i>Naturality index = log10 strictly natural / -log10 not natural</i> . Strictly natural and non-natural are 2 rasters based on the habitat map calculated by focal statistics in a 250m radius. Method based on the opposite of an urbanity index.	ArcGIS analysis	
	habitat quality	diversity of natural habitats	index	Shannon diversity index of natural habitat, based on a 7 natural habitat classification map.	Fragstats	[3]
	species diversity	flora presence	distribution area per species	614 layers of flora distribution based on habitat matrix and species observation.	ArcGIS analysis	

	species diversity	fauna presence	distribution area per species	25 layers of fauna distribution based on habitat matrix and species observation.	ArcGIS analysis
	habitat diversity	habitat presence	distribution area per natural habitat	46 layers of natural habitat distribution based on a detailed habitat map.	ArcGIS analysis

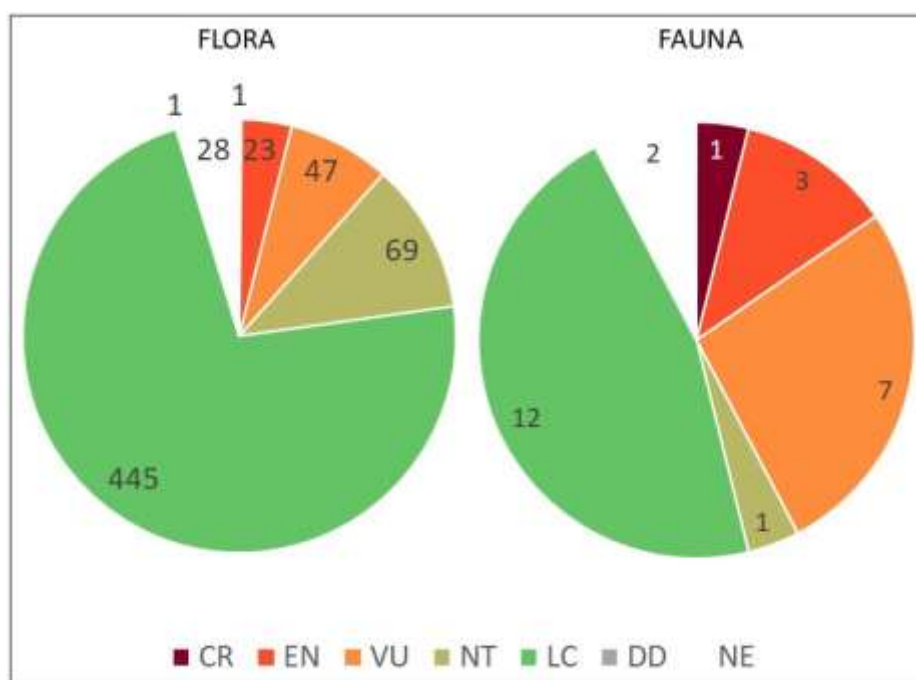


Figure S1. Species number in red list classification of endangered species (A: Fauna, B: Flora).

Table S2. List of selected species for the distribution of fauna.

Latin name	Class	Continuum
<i>Bombina variegata</i>	amphibian	Humid/ Forest
<i>Bufo bufo</i>	amphibian	Humid/ Forest
<i>Capreolus capreolus</i>	mammal	Forest / Crops
<i>Castor fiber</i>	mammal	Humid/ Forest
<i>Cervus elaphus</i>	mammal	Forest / Crops
<i>Emys orbicularis</i>	Reptile	Humid / Dry
<i>Felis silvestris</i>	mammal	Forest / Dry
<i>Hierophis viridiflavus</i>	Reptile	Forest / Dry
<i>Ichthyosaura alpestris</i>	amphibian	Humid/ Forest
<i>Lacerta bilineata</i>	Reptile	Dry / Bush
<i>Lepus europaeus</i>	mammal	Crops / Grassland
<i>Lissotriton helveticus</i>	amphibian	Humid/ Forest
<i>Martes martes</i>	mammal	Forest
<i>Meles meles</i>	mammal	Forest / Grassland
<i>Mustela erminea</i>	mammal	Crops / Grassland
<i>Natrix helvetica</i>	Reptile	Humid/ Forest
<i>Natrix natrix</i>	Reptile	Humid/ Forest
<i>Pipistrellus pygmaeus</i>	mammal	Forest / Urban grove
<i>Podarcis muralis</i>	Reptile	Forest / Urban grove
<i>Rana dalmatina</i>	amphibian	Humid/ Forest
<i>Rana temporaria</i>	amphibian	Humid/ Forest
<i>Remiz pendulinus</i>	Bird	Humid/ Grassland
<i>Salamandra salamandra</i>	amphibian	Humid/ Forest

<i>Sciurus vulgaris</i>	mammal	Forest / Urban grove
<i>Sus scrofa</i>	mammal	Humid/ Forest
<i>Vulpes vulpes</i>	mammal	Forest / Crops

Table S3. Selected weights for each feature in Zonation for tests.

		Layer weight	Layer number	Group weight	Pillar weight
pillar 1	Flora species	0.012	543	8.25	33.33
	RL flora species	0.024	71		
	Fauna species	0.23	14	8.25	
	RL fauna species	0.46	11		
	Habitat composition	0.359	46	16.5	
pillar 2	Structure & connectivity	4.71	7	33.33	33.33
pillar 3	ES	3.67	9	33.33	33.33

Table S4. Selected weights for each feature in Zonation for Geneva's GI.

		Layer weight	Layer number	Group weight	Pillar weight
pillar 1	Flora species	0.0365	543	25	100
	RL flora species	0.073	71		
	Fauna species	0.7	14	25	
	RL fauna species	1.4	11		
	Habitat composition	1.09	46	50	
pillar 2	Structure & connectivity	11.43	7	80	80
pillar 3	ES	2.22	9	20	20

Table S5. English translation of land use-land cover names used in biophysical tables, and naturality attribute.

LULC	French description	English Description	Naturality
1	Urbain dense	Dense urban areas	0
2	Forêts fermées de feuillus	Closed hardwood forests	1
3	Landes	Moors	1
4	Urbain diffus	Diffused urban areas	0
5	Végétation urbaine	Urban vegetation	0
6	Prairies sèches	Dry meadows	1
7	Autres milieux humides	Other wetlands	1
8	Forêts fermées de conifères	Closed coniferous forests	1
9	Cultures et prairies intensives	Intensive crops and meadows	0
10	Eaux calmes	Calm waters	1
11	Prairies d'altitudes	Altitude meadows	1
12	Forêts ouvertes	Open forests	1
13	Chemin	Path	0
14	Prairies extensives	Extensive meadows	1
15	Forêts humides	Rain forest	1
16	Eaux courantes	Running watercourses	1
17	Vigne	Vineyards	0
18	Chemin de fer	Railroad	0
19	Végétation arborée perturbée	Disturbed tree vegetation	0
20	Paroi débris affleurements rocheux	Rocky debris outcrop wall	1
21	Prairies humides	Wet meadow	1
22	Route	Road	0

23	Verger	Orchard	0
24	Glarier	Alluvium	1
25	Autoroute	Highway	0

Pollination Guild Table

Species: 20 most common species of pollinators in four families (Apidae, Andrenidae, Halictinae, Megachilidae) identified by Kleijn et al. [4] and present in Geneva.

Nesting types (NS_cavity and NS_ground): 1 indicates nesting in the habitat type. Based on Atlas Hymenoptera (www.atlashymenoptera.net/default.asp).

Seasonal activity (FS_spring, FS_summer, FS_autumn): 0 (not active) to 1 (highly active). Based on Atlas Hymenoptera.

Species weight: All species are weighted equally by default for relative abundance.

Foraging distance (Alpha): [meter] Based on *Atlas Hymenoptera*, and on Greenleaf et al.'s [5] formula using the distance between the wing bases, and on Gathman and Tschardt's [6] formulas using body size [7].

Table S6. InVEST pollination guild.

Species	NS_cavit y	NS_groun d	FS_sprin g	FS_summe r	FS_autum n	species_weigh t	alph a
Bombus terrestris	0	1	1	1	1	1	1500
Bombus lapidarius	0	1	0.4	0.4	0.2	1	1500
Andrena chrysosceles	0	1	0.4	0.4	0.2	1	260
Andrena flavipes	0	1	0.5	0.5	0	1	1150
Andrena haemorrhoa	0	1	1	0	0	1	373
Andrena carantonica	0	1	1	0	0	1	512
Bombus pascuorum	0	1	0.4	0.4	0.2	1	2300
Andrena fulva	0	1	1	0	0	1	315
Andrena dorsata	0	1	0.5	0.5	0	1	650
Lasioglossum calceatum	0	1	0.5	0.5	0	1	1000
Lasioglossum malachurum	0	1	0.5	0.5	0	1	600
Bombus hypnorum	1	0	0.5	0.5	0	1	288
Osmia rufa	1	1	1	0	0	1	600
Bombus pratorum	0	1	0.5	0.5	0	1	674

Andrena nitida	0	1	1	0	0	1	288
Andrena minutula	0	1	0.5	0.5	0	1	112
Bombus hortorum	0	1	0.4	0.4	0.2	1	604
Lasioglossum politum	0	1	0.5	0.5	0	1	14
Lasioglossum morio	0	1	0.4	0.4	0.2	1	69
Andrena cineraria	0	1	1	0	0	1	300

Pollination Land Cover Attribute table

Nesting types (N_ground, N_cavity): (0–1) index of nesting availability in the ground or in cavities, based on Gardner [8] and Pfiffner and Müller [9] (Magnin, 2017).

Seasonal flower abundance (F_spring, F_summer, F_autumn): (0–1) relative abundance of flowers per season. Based on the land cover map and Delarze [7,10].

Table S7. InVEST pollination land cover attribute.

LULC	Description	N_ground	N_cavity	F_spring	F_summer	F_autumn
1	Urbain dense	0	0	0	0	0
2	Forêts fermées de feuillus	0.2	0.5	0.8	0.1	0.1
3	Landes	0.2	1	1	0.3	0
4	Urbain diffus	0.7	0.8	0.7	0.6	0.8
5	Végétation urbaine	0.5	0.7	0.1	0	0
6	Prairies sèches	1	1	0.8	0.6	0
7	Autres milieux humides	0	0	0.2	0.3	0.1
8	Forêts fermées de conifères	0.5	0.3	0.6	0.3	0
9	Cultures et prairies intensives	0.3	0	0.4	0.5	0.4
10	Eaux calmes	0	0	0.1	0.1	0
11	Prairies d'altitudes	0.4	0.2	0.2	0.2	0.2
12	Forêts ouvertes	0.2	0.3	0.4	0.3	0.4
13	Chemin	0	0	0	0	0
14	Prairies extensives	1	1	0.4	0.6	2
15	Forêts humides	0.2	0	1	0.5	0.2
16	Eaux courantes	0	0	0.1	0.1	0
17	Vigne	0.2	0	0.2	0.3	1
18	Chemin de fer	0.5	0.3	0.1	0.6	0.5
19	Végétation arborée perturbée	0.5	0.8	0.5	1	0.3
20	Paroi débris affleurements rocheux	0	0	0	0	0
21	Prairies humides	0.4	0.3	0.3	0.4	0.2
22	Route	0	0	0	0	0
23	Verger	0.8	1	0.5	0	0

24	Glarier	0	0	0	0	0
25	Autoroute	0	0	0	0	0

Carbon pools biophysical table

Based on Switzerland's Greenhouse Gas Inventory 1990-2017 [11].

Table S8. Carbon pools (carbon density in aboveground biomass, belowground biomass, soil, and dead matter) for each LULC class.

lucode	LULC_name	C_above	C_dead	C_below	C_soil
1	Urbain dense	0	0	0	0
2	Forêts fermées de feuillus	134.51	8.10	8.70	55.4
3	Landes	6.5	0	0	68.23
4	Urbain diffus	0	0	0	0
5	Végétation urbaine	15.43	0	0	53.4
6	Prairies sèches	4.98	0	0	59.4
7	Autres milieux humides	6.5	0	0	68.23
8	Forêts fermées de conifères	134.51	8.10	8.70	55.4
9	Cultures et prairies intensives	3.51	0	0	49.91
10	Eaux calmes	0	0	0	0
11	Prairies d'altitudes	4.98	0	0	59.4
12	Forêts ouvertes	134.51	8.10	8.70	55.4
13	Chemin	0	0	0	0
14	Prairies extensives	4.98	0	0	59.4
15	Forêts humides	134.51	8.10	8.70	55.4
16	Eaux courantes	0	0	0	0
17	Vigne	5.36	0	0	53.4
18	Chemin de fer	0	0	0	0
19	Végétation arborée perturbée	20.45	0	8.7	55.4
20	Paroi débris affleurements rocheux	0	0	0	0
21	Prairies humides	6.4	0	0	68.23
22	Route	0	0	0	0
23	Verger	22.73	0	0	64.76
24	Glarier	7.16	0	0	26.31
25	Autoroute	0	0	0	0

Nutrient retention biophysical table

Nutrient load (Load_n): Based on [12].

Maximum retention efficiency (eff_n): (0–1) based on Salata et al. [12].

Critical length (Crit_len_n): Set to 150 for grass and forest areas, and to the pixel size for all other land cover types [13].

Table S9. InVEST NDR biophysical table.

lucode	LULC_desc	load_n	eff_n	crit_len_n
1	Urbain dense	0	0	5
2	Forêts fermées de feuillus	6	0.8	150

3	Landes	4	0.6	150
4	Urbain diffus	13	0	5
5	Végétation urbaine	23	0.6	150
6	Prairies sèches	12	0.6	150
7	Autres milieux humides	4	0.4	150
8	Forêts fermées de conifères	6	0.8	150
9	Cultures et prairies intensives	12	0.6	150
10	Eaux calmes	15	0	5
11	Prairies d'altitudes	8	0.6	150
12	Forêts ouvertes	6	0.8	150
13	Chemin	13	0	5
14	Prairies extensives	12	0.6	150
15	Forêts humides	6	0.8	150
16	Eaux courantes	18	0	5
17	Vigne	33	0.4	150
18	Chemin de fer	0	0	5
19	Végétation arborée perturbée	23	0.6	150
20	Paroi débris affleurements rocheux	7	0.6	5
21	Prairies humides	12	0.6	150
22	Route	0	0	5
23	Verger	12	0.4	150
24	Glarier	7	0	5
25	Autoroute	0	0	2

Table S10. Parameters used for InVEST NDR model.

Threshold flow accumulation	200
Borselli k parameter	2
Subsurface critical length	200
Subsurface maximum retention efficiency	0.8

Sediment retention biophysical table

Cover management factor (usle_p): (0–1) 0.5 for urban, and 1 for all classes except agriculture [14].

Values for agricultural areas from Panagos et al. [15].

Support practice factor (usle_c): (0–1) [16].

Table S11. InVEST SDR biophysical table.

lucode	LULC_desc	usle_c	usle_p
1	Urbain dense	0	0.5
2	Forêts fermées de feuillus	0.0012	1
3	Landes	0.0219	1
4	Urbain diffus	0	0.5
5	Végétation urbaine	0.02652	0.5
6	Prairies sèches	0.0435	1
7	Autres milieux humides	0	1
8	Forêts fermées de conifères	0.0012	1
9	Cultures et prairies intensives	0.1384	0.9942

10	Eaux calmes	0	1
11	Prairies d'altitudes	0.0903	0.9942
12	Forêts ouvertes	0.0012	1
13	Chemin	0	0.5
14	Prairies extensives	0.0903	0.9942
15	Forêts humides	0.0012	1
16	Eaux courantes	0	1
17	Vigne	0.3527	0.9942
18	Chemin de fer	0	0.5
19	Végétation arborée perturbée	0.0219	1
20	Paroi débris affleurements rocheux	0	1
21	Prairies humides	0.0435	1
22	Route	0	0.5
23	Verger	0.1232	0.9942
24	Glarier	0	1
25	Autoroute	0	0.5

Table S12. Parameters used for InVEST SDR model.

Threshold flow accumulation	200
Borselli k parameter	2
Borselli IC0 parameter	0.5
Maximum SDR value	0.8

Table S13. The top 30% areas based on a prioritization of biodiversity pillar covered 69.6% of species and habitats. Pillars in the scenario with all pillars combined have equal weights.

best %	% of biodiversity covered with the biodiversity pillar	% of biodiversity covered with all pillars combined	% of biodiversity covered with the ES pillar	% of biodiversity covered with the structure pillar
0	0.0	0.0	0.0	0.0
5	11.5	12.0	14.4	10.2
10	24.9	25.7	26.0	19.3
15	39.6	40.0	36.9	27.6
20	53.9	52.3	47.3	35.9
25	62.8	60.8	55.6	44.1
30	69.6	66.7	61.8	50.1
35	75.8	71.2	66.8	55.4
40	81.1	75.1	71.0	60.6
45	85.3	78.5	74.8	65.4
50	89.0	81.6	78.3	69.9
55	91.4	84.6	81.6	74.2
60	93.2	87.4	84.6	78.3
65	94.0	89.8	87.4	82.3
70	94.6	92.1	90.0	86.1
75	95.1	94.2	92.5	89.4
80	96.7	96.1	94.7	92.5
85	98.3	97.6	96.6	95.2
90	99.5	98.9	98.2	97.4
95	100.0	99.8	99.3	99.1
100	100.0	100.0	100.0	100.0

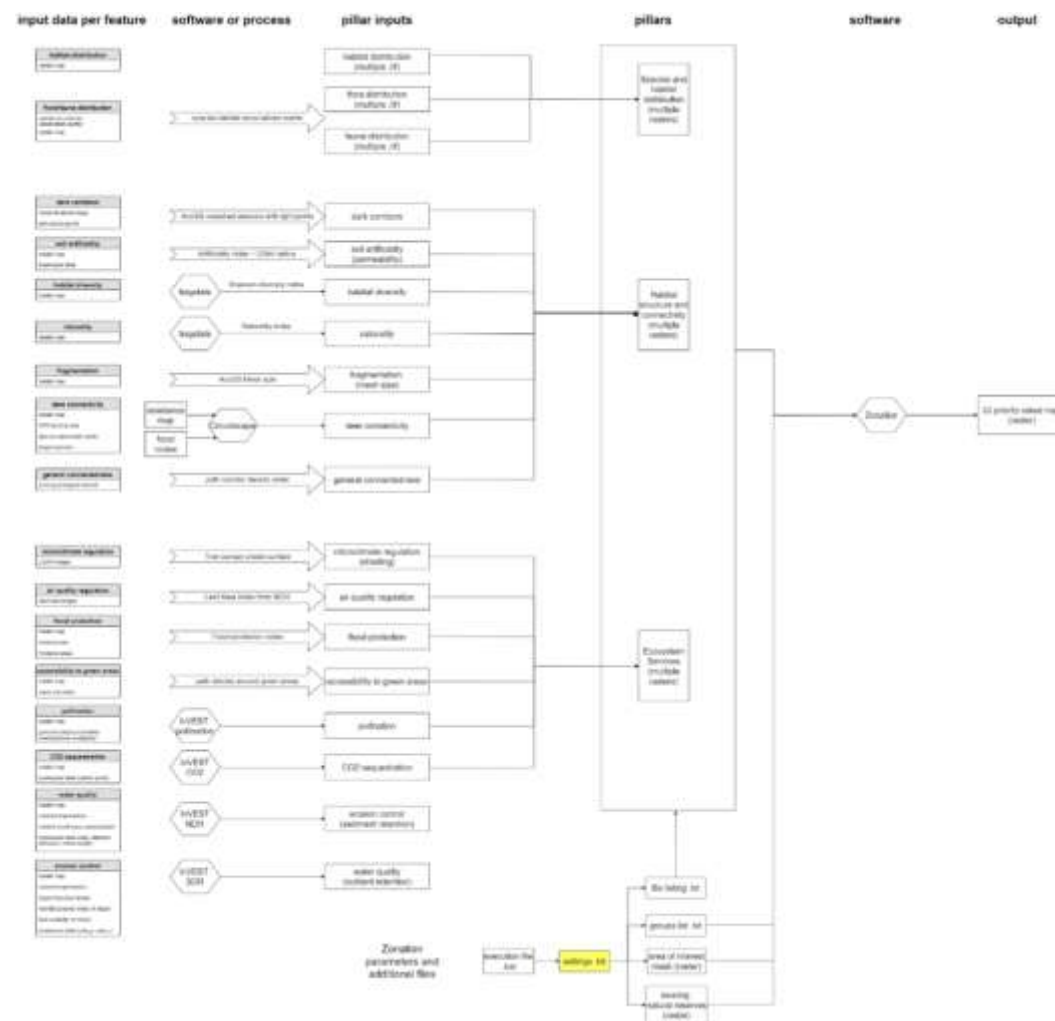


Figure S2. GI inputs and mapping flowchart. Attribution of feature weights and selection of prioritization parameters in Zonation are done through the “settings” file (in yellow).

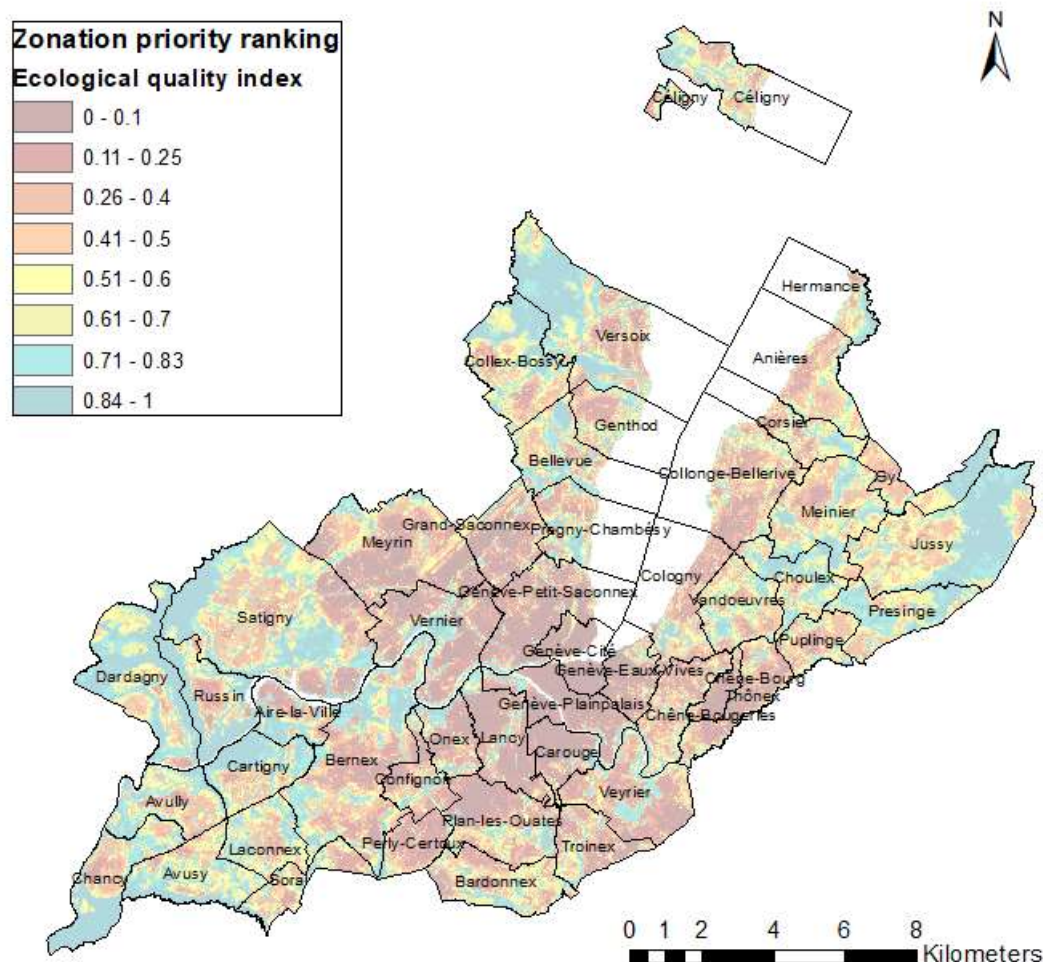


Figure S3. Zonation priority ranking (Figure 2 in article) with names and borders of communes.

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