AN ECOLOGICAL-ECONOMIC FRAMEWORK TO PROJECT FUTURE IMPACTS OF URBANIZATION ON BIODIVERSITY USING PARCEL SCALE DATA AND ENDOGENOUS LAND USE (PLAN) ZONING

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ABSTRACT

Urbanization is currently a major threat on biodiversity due to the direct destruction and fragmentation of natural and semi-natural habitats and also to the indirect impacts caused by urban areas beyond their limits. There is thus an urgent need to examine the current and future potential impacts of urban areas on biodiversity. Global analyses of this issue have often failed to integrate the multi-scale dimensions of urban threats on biodiversity and suffer from a lack of precise data on both socio-economic conditions and biodiversity inventories. In this study, we assess the potential impacts of current and future urbanization on high diversity sites and their associated species of five taxonomic groups across the entire French Mediterranean region. In order to do so we adapt a land-use change (LUC) model to predict future urbanization over a 20 years period. Using a 100 meter grid scale, we developed a multi-level approach based on three impacts of urban development: the direct consumption of high diversity sites, the indirect urban effects on the surrounding area over a scale of 2km and a scale of 50km. Our model predicts that 464 sites (35% of the total number of sites) will be concerned by urbanization (i.e. at least one hectare predicted to be built between 2006 and 2030). 43 sites (3.3% of the total number of sites) may lose 10% or more of their surface area to urbanization. We found that the impacts of urban area and urban growth and the biodiversity elements impacted differ among the three different pressure indicators in terms of surface area and localization of sites, number and nature of species impacted and variation of these patterns between the two dates. Mammals are the species the least threatened by urban pressure. In general, most of the sites under pressure are located in the coastal part of the study region and are of smaller surface area than average.

Keywords: Biodiversity, prospective, urbanization, land-use change, Mediterranean region

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INTRODUCTION

Rapid human population growth over the last century has resulted in urban areas covering about 2% of total land surface (Grimm *et al.*, 2000). As human populations continue to grow major urban areas will continue to expand (Meyer and Turner, 1992). Although the concentration of people in major cities and the densification of new constructions can help to protect natural and agricultural resources elsewhere (Forman, 2008), urbanization represents a major threat to biodiversity across the world (Wilcove *et al.*, 1998; Chapin *et al.*, 2000; McDonald *et al.*, 2008).

Urbanization is of major concern for biodiversity conservation for several reasons. First, the intense artificialisation of habitats makes changes associated with urbanization to be among the least reversible of land-use change. Second, because urbanization is often concentrated in areas of high net primary production which are also areas with very high species richness (Balmford *et al.*, 2001; Araujo, 2003; Vazquez and Gaston, 2006; Luck, 2007), its effects on biodiversity are much greater than randomly expected. Third, urban and suburban areas are mostly occupied by exotic species which thrive in habitats where human presence is important and where human activities have removed the native dominant species. Hence, the number of non-native species is high and the contribution of urban (and suburban) areas to the conservation of global biodiversity is very low (McKinney, 2002). Finally, urban impacts on biodiversity can extend far beyond the city limits (Luck *et al.*, 2001; Forman, 2008). Indeed, urban areas threaten ecosystems as a result of both direct habitat conversion (Clergeau *et al.*, 1998; McKinney, 2002) and through various indirect effects, e.g. land use change in the periphery of urban area, fragmentation of the territory by linear infrastructures associated with communication and transport among urban areas, waste generation and water pollution, and disturbances associated with recreational activities around urban areas (DeFries *et al.*, 2007).

There is thus an urgent need to pay close attention to the spatial distribution of urban areas and to predict its evolution in the future in relation to the distribution of biodiversity conservation interests. The potential impacts of urban spatial expansion on biodiversity have been studied across a diversity of scales ranging from the international and national level scale (*e.g.* (Theobald and Romme, 2007; Jenerette and Potere, 2010) to regional level effects, mostly associated with habitat fragmentation (Martinuzzi *et al.*, 2007; Lawson *et al.*, 2008; Manley *et al.*, 2009), and impacts observed in and around particular urban centers (Jarrige, 2004; Wu *et al.*, 2007). One of the recurrent difficulties is to assess the relative effects of the diversity of impacts caused by urbanization because it can range from destruction of habitats to indirect effects associated with pollution or noise caused by human proximity. Global analyses have often failed to support the multi-scale dimensions of urban threats on biodiversity and suffer from a lack of precise data on both socio-economic conditions and biodiversity inventories.

Over the past decades, several models have been developed to predict and quantify future land use and land cover for ecosystem impact assessment (Irwin and Geoghegan, 2001; Veldkamp and Lambin, 2001; Parker *et al.*, 2003; Verburg *et al.*, 2004), mainly in land-use-change (LUC) models. LUC models aim to show how or where irreversible changes will arise in the future, in order to adapt current public policy (Lambin, 1997; Conway and Lathrop, 2005). Urbanization can be modeled through various approaches (Irwin 2010) from complex descriptions of urban expansion with many parameters describing multiple levels of land use change (Landis, 1995; Alberti, 1999; Fontaine and Rounsevell, 2009), to simplified models using a minimal set of parameters on a large scale (Batty, 1991; Fagan *et al.*, 2001; Rouget *et al.*, 2003). In general, most of the fine-scale modeling studies have only been implemented for a single city (*e.g.* (Taylor *et al.*, 2007; Jenerette and Potere, 2010). A similar modeling framework at regional scale would allow a more precise understanding of the interactions between micro-level parameters and macro-level land use change and thus help assess the potential impacts of future urban spread on biodiversity.

In this study, we assess the potential impacts of current and future urbanization on high biodiversity sites and their associated species across the entire Mediterranean region of southern France. Future urbanization is forecasted using a land use change (LUC) model at 20 years horizon with 100 meter grid cell. In order to account for a range of different urban threats, we developed a multi level approach based on three urban pressure indicators from precise urban arrangements on a local scale, to global human density impacts over a larger scale. To do so, we examined urban development and its potential impact in three ways namely the direct consumption of high diversity sites, and indirect urban effects on the surrounding area over a scale of either 2km or 50km.

METHODS

Study area

The study region covers 59 660 km² of the Mediterranean region of southern France (Fig. 1). It represents two regional administrations: the *Languedoc-Roussillon (LR)* region to the west of the Rhône valley as far as the Spanish border and the *Provence-Alpes-Côte d'Azur (PACA)* region to the east and as far as the Italian border. These two regions have 11 administrative subdivisions (county or "*départements*") and 2508 municipalities, each of which has its own local land use plan. The study region is part of one of the major World hotspots of biodiversity (Medail and Quezel, 1999; Myers *et al.*, 2000; Shi *et al.*, 2005), but is also one of the most transformed regions with a marked landscape diversity due to geological and climatic variability and a long history of human land-use - notably extensive agro-sylvo-pastoral practices and cultivation (Thompson, 2005; Blondel *et al.*, 2010). The main landscape types which occur in this region are coastal landscapes with lagoons, marshes, cliffs and dunes, lowland garrigues often as a mosaic with cultivated areas, vast areas of vines, extensive upland limestone plateau areas, and hilly or mountainous landscapes on granite, schist or limestone in the southern tip of the Massif Central, the south-eastern Pyrenees and the pre-Alps. The Mediterranean region is currently undergoing massive coastal urbanization and infrastructure development (G. Benoit and Comeau A., 2005). The French Mediterranean region currently has the most rapidly growing human population of France (Bessy-Pietri, 2000), particularly in lowland areas close to the coast. This has entrained rapid spread of urbanization around towns and villages and coastal development associated with tourism.

Data

Biodiversity data

As part of the national inventory of high ecological value sites (*Zones Naturelles d'Intéret Ecologique Faunistique et Floristique* or ZNIEFF), a list of determinant species of conservation interest has been elaborated in each region of France and high diversity sites based on the presence of these species designated. This inventory is validated by a regional scientific council (*Conseil Scientifique Régional du Patrimoine Naturel* or CSRPN). We used the inventory of the two administrative regions as a basis for our study. To identify the list of determinant species, regional specialist organizations weighted and noted each species of a given taxonomic group to define their conservation interest (INPN, 2006). The main criteria used for this purpose were local rarity, quantified by the number of distinct localities where a species has been recorded in the region, and the regional responsibility, quantified in relation to the number of other regions in France where the species occurs. Additional criteria such as international, national, or regional protection status were also considered. For the purpose of this study we used taxonomic groups for which we had sufficient information on the regional distribution and abundance, namely 1040 vascular plants, 28 mammals, 20 herptiles (reptiles and amphibians), 86 birds and 16 fishes. Following the inventory of these species, 1315 high diversity sites (18.2% of the surface of the study region) were designated by the regional operators (Fig. 1). Only species reproducing on a given site were considered to be present. Site boundaries were delimitated on the basis of the distribution of determinant species and minor adjustments made to species composition based on expert consultation.

Urbanisation data

For the whole study area, we used four kinds of databases:

- The 2008 "built-up" layer of BD TOPO®/RGE Geodatabase (*IGN Institut Géographique National*) which is the topographic component of French RGE (literally "*Frame of reference at large scale*"). This layer contains around 300 000 polygons for each administrative subdivision. We use aggregated BD TOPO® data for undifferentiated building. We considered a grid cell as built-up if at least 2.5% of its surface intersected with built-up polygon.

- The Land Use Plan Geodatabase was obtained from the two nationally administered regional environmental agencies (*Direction Régionale de l'Environnement, de l'Aménagement et du Logement*), which are in charge of the legal control of town and country planning policy. They have a digitalized land-use plan (LUP) of each municipality which are harmonized for comparative use. The resulting regional geodatabase is called a "Generalized LUP" and is updated every two years. For the purpose of this study, we reclassified LUP's into three types of zoning, indexed hereafter by z: high urban density zoning (URB), future Urban/Activities zoning (FURB), isolated houses with agricultural/natural zoning (NONBDEV). Since LUPs are not made for most rural and uninhabited municipalities, we used the Corine Land Cover Database (CLC 2006) to define three zones similar to those defined above (this represents 3% of the regional population and 27% of the total number of municipalities).

- In order to tune some parameters of the simulation model (see section 3.2), we used a cadastral vector database available for the PACA region only. This database contains two important pieces of information. First, it denotes parcel boundaries (3 millions polygons) and house delimitation (1.6 millions polygons; "*Plan Cadastral Informatisé*"). Second, it provides house and owner characteristics (fiscal database commonly called MAJIC II) that allows to identify for each residential house the date of construction (Geniaux *et al.*, 2009)

• At municipal level, we used census data of population, housing, activities and employment (INSEE). Following (Geniaux *et al.*, 2005) and (Geniaux, 2010), we built a classification of municipalities useful for statistical descriptive analysis of urban density dynamics and LUP policies. This classification crossed a municipal total houses classification with a municipal surrounding population in the 50 km neighborhoods classification and resulted in 11 effective levels indexed hereafter by *c*[3].

Information of these four databases has been reported on a 100 meter grid cell with 6 million of cells for the two regions.

Urban model

Our model aims to forecast land use change (LUC) over a 20 years horizon using the 100 meter grid cell. The global design of the simulation model is illustrated in Fig. 2. The core of the model is based on the probability to be built for a non-already built cell. Then, in order to locate the effective new built cells, local probability thresholds are calculated for each municipality based on two external information items. The first one is a forecast of total housings number on municipal levels in next 20 years. The other one is an estimate of the proportion of housings for each land use plan zone z in each municipality class c based on three local urban parameters, coming from a statistical analysis of 1990-1995 building dynamics at parcel level for the PACA region.

Our model distinguishes itself from previous works on LUC model by using information on land use plan for more than 1500 municipalities. As noted by (Irwin, 2010), almost all LUC models do not use geographic data on land use plan and are based on a theoretical framework in which land market and land use are not regulated by public institutions. Our model integrates vectorized geographic information on public regulation in its estimation of land use change probability as well as for determining the number of houses of future converted parcel.

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[3] Municipal total houses was classified into 4 levels (0-200,200-2000, 2000-10000,>10000). Surrounding population of each municipality was estimated using a kernel smoother function of distance between municipalities and classified in 4 levels using quartiles. $\sum_j e^{-distance_{ij}/10)^2} \ \forall j \ with \ distance_{ij} < 50km$

Probability of land use conversion

Our model estimates for each cell g with no house ($Y_g = 0$) the probability to be developed for residential use ($Y_g = 1$) knowing a set of covariable *X* and the type of LUP zone z of each cell g. In order to estimate such probability in a spatial and large database context, we used a semi-parametric spatial generalized additive logit model (Hastie and Tibshirani, 1993; Wood, 2006; Geniaux and Napoleone, 2008) to specify a parametric GLM probit[4]. Non linear covariates $X2_g$ has been split into two or three linear parts and integrated in a full parametric GLM logit that can be expressed as:

$$P(Y_g = 1|X, z) = \beta_0 + \beta_1 clc90 + \beta_2 sl + \beta_3 zone + \beta_4 nsd + \beta_5 lpa$$
$$+\beta_6 duc1 + \beta_7 duc2 + \beta_8 dsr1 + \beta_9 dsr2 + \beta_{10} pr1 + \beta_{11} pr2 + \beta_{12} dmr1$$
$$+\beta_{13} dmr2 + \beta_{14} area + \beta_{15} apr + \beta_{16} WYp + \epsilon_g \quad (1)$$

Table 1 describes labels and descriptive statistics of each covariate of final model. Due to the very large number of grid cells, model (1) has been estimated separately in each of the 11 administrative sub-regions (French county or "*department*") of the studied area (around 500.000 cells in each county). In order to account for the heterogeneity of urbanization process and density between types of zones z, model (1) has been estimated separately for each type of zoning z and for each county. Finally, we obtained for each cell g the probability to be developed before 2030 noted $\hat{P}(Y_g = 1|X, z)$.

From probability to house building

To convert probability estimates into effective land changes, we used local probability thresholds depending on constraints on two scales: on a municipality scale, the total number of housings and on the LUP zones scale, the housing density. These two constraints based on information external to the model (1) are constructed as follows:

First, we used a municipal forecast of the total number of housings for 2030, noted HD_i . Total number of municipal housings can be mainly explained by sequences of past number of housings (we used the four preceding census), by the county, and by inhabitants and

[4] A Generalized Additive Model (Hastie and Tibshirani 1990) is an extension of the Generalized Linear Model (GLM) in which the linear predictor is specified as the sum of smooth functions of regressors. We obtain a geoadditive logit model by integrating, in a smoothing function, longitude y and latitude x, and by using a logistic distribution. It can be expressed it as :

$$P(Y_g = 1|X1, X2, x, y, z) = \beta X1_g + \sum_m s_m(X2_g) + s(x_g, y_g) + \epsilon_g \quad (2)$$

The GAM logit model (2) has been used i) to identify non linearity in continuous covariables, in particular distance and residential density covariates and ii) to obtain a final specified model that flatten as possible the spatial smoothed terms . This specification process has been done using various subsample of 100 000 cells randomly chosen between the 6 millions of cells of the study area.

employments in the surrounding 50 km. HD_i is estimated with a least square percentage error models (Tofallis, 2009). Moreover, we used strata in order to have different coefficients values for 7 types of municipalities according to the level of population (7 levels of number of housing of the preceding census noted $CHD_{i,t-1,k}$:

$$HD_{t,i} = \beta_0 + \beta_1\ County + \sum_{k=1}^{7} \sum_{s=1}^{4} \alpha_{k,s} CHD_{i,t-1,k} \times [HD_{i,t-s} + spop_{t,i} + slab_{t,i}] + \epsilon_i \quad (2)$$

Equation (3) is estimated with a weighted least square in which the weights are equal to the inverse of the lagged endogenous $1/HD_{t-1,i}$ that correspond to a Least Squares Percentage Regression (LSPR) that minimize the square of the relative errors (Tofallis, 2009). This type of regression is necessary to avoid that large municipalities may have too much influence on the results and lead to high relative errors for small municipalities. Coefficient estimates of (2) allow predicting HD_i at *t+s*. In the next step, $\bar{P}(Y_g = 1|X)$ is the local probability threshold so that the number of building realization is equal to $\hat{HD}_{i,t+s}$.

Second, In order to identify on an infra-municipal level the precise threshold for realization of land use change probability for each type of land use plan zones, we used statistics on housing at parcel scale by type of zoning *z* and by type of municipality *c* for recently built houses (after 1990) in PACA region for which the date of construction is known.

- α_{1c} is the proportion, for each type of municipality *c,* of new housings after 1990 that have been built in previously unbuilt parcels. It allows estimating the proportion of future housing of the municipality that will be located in previously unbuilt parcels. We obtained:

$$\tilde{HD}_{i,t+s} = \alpha_{1c} \times \hat{HD}_{i,t+s} \quad with\ i \subset c \quad (4)$$

- α_{2cz} is the proportion of housings built after 1990 by type of LUP zones *z* for each type of municipality *c*. It allows distributing $\tilde{HD}_{i,t+s}$ between various LUP zone types of municipality *i* depending on the area of the LUP zone $S_{i,z}$. Thus:

$$\tilde{HD}_{i,z,t+s} = \alpha_{2cz} \times \frac{S_{i,z}}{\sum_z S_{i,z}} \tilde{HD}_{i,t+s} \quad (5)$$

- α_{3cz} is the number of housings by hectare by LUP zone *z* and by type of municipality *c*.

The final number of new houses for the unbuilt cells *g* which have a conversion probability higher than the local threshold noted $H_{g(c,z)}$ is given by:

$$H_g(c,z) = \alpha_{3cz}\ \ if\ \ \hat{P}(Y_g = 1|X) > \bar{P}(Y_g = 1|X) \quad (6)$$

Moreover, $\forall g \;\; \bar{P}(Y_g = 1|X)$ must verify the two following conditions:

$$\forall i \;\; \sum_{g \subset i} H_g(c,z) \leq \tilde{HD}_{i,t+s}$$

$$\forall z \;\; \sum_{g \subset z \subset i} H_g(c,z) \leq \tilde{HD}_{i,z,t+s}$$

Data analysis

Sites considered as threatened

We assessed three urban pressure indicators at the site level. Pressure 1 (*P1*) corresponds to the predictable consumption for housing inside each site. *P1* is calculated only for the year 2030 and is equal for each site to the percentage that could be newly built in 2030. A site is considered threatened if *P1* > 10%. Pressure 2 (*P2)* corresponds to the smoothed impact of urban area at a local scale in the nearby neighborhood of each site (2km). For each cell *g,* we calculated *p2* as the sum of the number of built-up cells in a 2 km buffer zone weighted by their distance to the cell in question (weights are estimated using a Gaussian kernel smoother[5] with a bandwidth *h*=0.8 km). *P2* is equal to the mean value of *p2* for each site. A site was considered as threatened if *P2*> 85's percentile of all sites in 2008. Pressure 3 (*P3)* corresponds to the smoothed impact of urban area at a global scale in the large neighborhood of each site. First we calculated *p3* as the number of built cells *g* in each square of 1000x1000 meters. For each site we calculated *P3* as the mean value of *p3* in a 50 km buffer zone weighted by the distance between the 1000 meters square and site centroïd (weight are estimated using a Gaussian kernel smoother with a bandwidth *h*=25 km). Mean values were preferred to totals because they limit border effects due to the large scale nature of this indicator. A site was considered as threatened if *P3*> 85's percentile of all sites in 2008. For each pressure indicator, we calculated the number and mean and total percentage area of threatened sites, and the mean number of species per threatened site.

An important methodological point of this study is the use of a smoothed function for pressure indicators 2 and 3. Although several studies have already investigated the indirect

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[5] We used $\sum_j e^{(distance_{ij}/h)^2}$ for all *j* for which distance between *i* and *j* is less than the buffer distance; *h* is the bandwidth.

impact of human presence on biodiversity surrogates using a buffer zone (Harcourt *et al.*, 2001; Vazquez and Gaston, 2006; Luck, 2007), our method allows us to account for a pressure which intuitively decreases in relation to distance from urbanized cells.

Assessing threat levels for species

For each taxonomic group, we investigated the number of threatened species according to the three urban pressures. A species was considered as threatened if more than 30% of its range (number of sites) is under pressure. Fish species are not considered for the P1 indicator since they are present in watercourses which are never considered as built-up. In order to assess the relationship between urban impacts and species rarity, we calculated the number of sites of the species (*i.e.* the range of the species) between those considered as threatened and the others. In order to assess the impact of urbanization beyond to the species range threshold, we also calculated for each taxonomic group the mean percentage of threatened sites for each species. Finally we mapped threatened sites and analyzed the number of sites and species that incur several pressure levels.

RESULTS

The LSPR model (3) for forecasting municipal population in ten years provides a 0.9954 adjusted R2 (detailed results of this model are given at URL http://www.cefe.cnrs.fr/ecopop/pdf/Vimal/Urbanisation_Model_Results.pdf). Table 2 gives an overview of the logit model results by type of zoning *z* (URB, FURB, NONDEV) and for the 11 counties (see also the URL above for detailed results of the 33 logit models). We present the size of sample, the percentage of thru one and thru zero, and the value and significance of three coefficients (the closed neighboring urban density β_{WYp} , the distance to small road β_{dsr}, the dummy "dominant land cover equal meadow in 1990" $\beta_{CLC90=23}$). Results are particularly stable with no sign reversal for the three coefficients (others coefficients present the same regularity). The only exception is the effect of the dominant Corine Land Cover (CLC90) that can change among counties. For example, the land cover type meadow ($\beta_{CLC90=23}$) is reversed for the Lozère (48) county which is the less inhabited county of France and where meadows are the almost ever dominant land cover. The effect of closed neighboring urban density (β_{WYp}) is very stable, particularly for zoning URB and FURB. This coefficient decreases generally for most of the inhabited counties (counties 13, 06, 83, 34 and 84 with more than 150 inhabitants/km2). We can note that the model fits better the built cell for URB (around 95 % of True one) and FURB zoning (around 75 % of True one) than the unbuilt cell. For NONBDEV zoning, it becomes naturally easier to predict unbuilt cells (around 98 % of True zero), but with only around 30 % of True one. We present and comment in Table 3 the urban model results in detail only for the *Vaucluse (84)* county and for NONBDEV zoning. The main driving factors influencing the probability of urbanization (Table 3) are location (in suburbs of greatest cities), infrastructure density (road density within the cell) and housing density in vicinity (frame of built area in contiguous cells WPy). More precisely, the effects which reduce the probability of urbanization are slope (*sl=3*) and enforced conservation policy (*lpa=Y*). The covariates which have the most positive effect on the probability of urbanization concern the ratio of road inside the cell <10% (*pr1*), the ratio of built surface in contiguous cells (*WYp*) and to a lesser degree the location in the second commuter belt.

In 2008, 7.5% of the territory of the study was urbanized. Our model predicts that additional 1.3% will be urbanized for house building by 2030. In terms of Corine Land Cover classes, 30% of new urban areas will occur in already built-up areas, 57% on agricultural land (notably in heterogeneous agricultural zone and permanent culture) and 12% on natural and semi natural areas (principally in forest and open environment).

Within the delimited sites, there is an average of 8.5 determinant species per site. The mean surface area of sites is about 823 hectares. The mean number of sites per species is about 7.5 for plants, 19.6 for mammals, 21.8 for birds, 18.6 for fishes, 26.8 for herptiles.

The frequency distribution of sites in relation with different pressures in 2030 varies among the three pressure indicators (Fig. 3a). According to pressure indicator 3, the pressure is more widely distributed among the sites. The frequency distribution of species in relation with the percentage of their range which is threatened also varies among the three pressure indicators (Fig. 3b). The high number of species which have 100% of their range threatened is probably due to the rare species. Indeed, a species present in only one site is threatened either at 100% either at 0% of it range. However, note that, according to the pressure 1, 10 species are predicted to have 100% of their range threatened in 2030.

Our model predicts that 3512 hectares (*i.e.* number of grid cells which will be built) of high diversity sites will be impacted by urbanization by 2030. Thus, 464 sites (35% of the total number of sites) will have at least one hectare urbanized between 2006 and 2030. The mean surface area of these sites is about 1255 ha which is significantly higher than the mean surface area of all sites (Student $t = 5.6571$, $p < 0.001$). However, only 43 sites will have more than 10% of their surface area urbanized in 2030 (Table 4). The surface area of these sites is low (a mean of 88 ha) and only 0.4% of the total area of high diversity sites is concerned. Only 36 plant species, one bird and one herptile species are threatened by direct urbanization. Given the significant low value of the mean number of sites per species for plants (4.7 sites), the species concerned are rarer than the species which are not threatened (*i.e.* their mean number of sites is lower). Mammals are the least impacted in terms of the mean percentage of threatened sites per species.

According to pressure indicator 2, 198 sites with a mean surface area of 219 ha, representing 4% of the total surface area of sites of conservation interest, are currently threatened by urbanization (Table 3). For each taxonomic group, the species concerned are not rarer than the others. Mammal and herptile species are the least impacted in terms of the mean percentage of threatened sites per species. The most impacted are fish species. In 2030, our model predicts an increase in 31% of the number of threatened sites (265 sites). The mean surface area of threatened sites increases from 178 to 213 ha, hence, the surface area of newly threatened sites will be higher in 2030. Based on our thresholds, approximately half (43.8%) of all fish species will be threatened. The fact that the mean number of sites of the threatened species increases for bird species means that the species newly impacted are more widely distributed than those in 2008. In contrast, for herptiles newly impacted species are rarer than those impacted in 2008.

According to pressure indicator 3, 198 sites with a mean surface area of 400 ha, are threatened in 2008. This represents 7.3 % of the total surface of sites of high conservation interest. No mammal species are threatened and threatened species are not rarer than species unthreatened except for herptile species. In 2030, our model predicts an increase in 48% of the number of threatened sites (293 sites). The mean surface areas of these sites increases from 400 to 546 ha, hence, the surface area of newly threatened sites will be higher in 2030. Based on our thresholds, approximately half (47.7%) of the fish species will be threatened. The mean number of sites of threatened species is similar to that in 2008, except for herptile species which show an increase from 5.3 sites per species in 2008 to 30.1 sites per species in 2030. Mammal species are the least impacted in term of the mean percentage of threatened sites per species. Birds and herptiles have the highest percentage of threatened sites.

For pressure indicators 1 and 3 at the two dates, the mean number of species per threatened site is not significantly different from the mean number of species of the other sites. It is significantly lower for the pressure 2 at the two dates (7.2 species per site).

In 2030, 38 sites of high conservation interest will be threatened by urbanization according to both P1 and P2 (*i.e.* 83% of the sites threatened under P1 are also threatened under P2). 125 sites will be threatened simultaneously by pressure 2 and 3, and 29 sites will be threatened by pressure 1 and 3. 28 sites are common to all three pressure indicators. 32 plant species and 1 bird species are considered as threatened for all three pressure indicators, while 173 plant species, 10 bird species, 3 fish species and 3 herptile species are considered as threatened for at least two pressure indicators.

Overall, the majority of sites under pressure for each pressure indicator are situated in the coastal part of the region (Fig.4). There are nonetheless some differences in terms of localization of the sites among the three pressure indicators. For P1 and P2, some threatened sites are localized in mountain areas (in the north of the study region) while for P3, threatened sites are aggregated around urban poles in the lowland plains, near the coast and in the Rhône valley. New threatened sites in 2030 occur close to those already concerned in 2008 for P3 while they are more dispersed for P2.

DISCUSSION

Our analysis provides a mean of assessing the direct and indirect threats of urbanization on biodiversity at a regional scale. To our knowledge, this is the first study to do so for such large territory and at a so fine grained scale. The three pressure indicators are highly complementary and range from precise quantification of land consumption to the pressure associated with human presence in a 50 km radius. Our study illustrates a diversity of potential impacts of urban spread on sites of high conservation interest and their associated species in the French Mediterranean region of southern France.

For future threats, our model combines demographic forecast at municipal level, and spatial forecast of new built location at infra-municipal level. The main improvement of our model is the infra-municipal spatial forecast that allows to take into account the location of new built in NONBDEV zoning that may have the most influential threat inside ZNIEFF or in closed neighboring of ZNIEFF (pressure 1 and 2). Even if LUP changes are mainly driven by land market and by land owner anticipation on policy change (McMillen and McDonald, 1991), the evolution of LUP is generally made by changing rules on a set of cells. In general, contiguous zones with numerous cells with high probability of change constitute the chosen sets. Isolated cells with high probability will likely stay unbuilt because the cells will stay in NONBDEV zoning in the mid-term. At this stage, model (1) takes this phenomenon into account only partially. The spatial dependence of the endogenous zoning, *i.e.* the probability to be built, would have beneficiate of a Spatial Autoregressive Regression (SAR) logit model that is unfortunately unusable with such large dataset. An extension of the Klier and McMillen (2008) methodology using generalized GMM for such latent class model may be useful for such rich spatial data context if combined with sparse matrix computation method. Here the identification of the drivers of urban spread was out of the scope of this paper. A further study would allow to assess precisely which are the drivers of urban impact on high diversity sites.

In terms of the numbers of threatened sites and species as well as the area of sites and their localization, the potential impacts of urbanization differ among the three pressure indicators. Most of the threatened sites of high conservation interest are of significantly smaller surface area than the other sites and occur primarily in the coastal region of the study area and the major Rhône river valley. Mammals are the least threatened species by urban pressure. This can be explained by their association with forest habitat in the study region (which is less affected by urbanization than open habitats and agricultural areas in our model) and are present in sites of generally larger surface area than average (Vimal *et al.*).

In this study, we presented results as mean values at the site level and using thresholds in order to identify sites and species under pressure. However, we recommend that particular attention is paid to all levels of threat, even for sites impacted for only one hectare and especially for pressure indicator 1. A population of a particular species will rarely systematically cover an entire site and could be destroyed or become threatened by a localized urban impact in large site. Furthermore, our analysis does not account for the sensibility of the species considered to urbanization threat which is likely to vary among and within taxonomic groups.

Direct consumption of sites through urban construction is certainly the greatest threat to biodiversity because it leads to an irreversible destruction of habitats and its associated species. In terms of direct destruction, our analysis illustrates that future urbanization could impact as much as 35% of the total number of sites (3512 hectares) of high conservation interest in our study region. However, less than 50 (3.2%) sites with very small surface area will have more than 10% of their surface area destroyed. The fact that species impacted in more than 30% of sites where they occur are rare plants is not surprising. Plants typically are species of small patch ecosystems with highly localized distributions and high levels of species turnover among sites. Even if the French law indicates that the ZNIEFF inventory of sites of high conservation interest should be taken into account before allowing an area to be urbanized, our study illustrates the high sensibility to urban pressure and direct habitat destruction of several sites.

Pressure indicator 2 refers to threats caused by immediate proximity of buildings. This pressure indicator thus depends on the local dynamics and spatial configuration of urbanization and some sites can be under pressure even though they may occur close to only small villages or dispersed buildings. This explains why there is no relation between the localization of the sites under pressure in 2008 and in 2030. The fact that fish are the most endangered species indicates that rivers (*i.e.* linear habitat configurations) will be increasingly threatened by adjacent urbanization. Indeed, a narrow site has more chance to be under pressure than a large shaped site. An increase in 33% of the number of threatened sites in 2030 shows the potential high level of pressure directly around the sites. This pressure illustrates the need to consider one high diversity site in its neighborhood environment. Some authors have already discussed the external reserves threats (DeFries *et al.*, 2007) and suggested the critical importance of creating buffer zones around them.

Pressure indicator 3 is less sensitive to the local dynamics of urbanization in that it provides information on a more global threat, due to urbanization in a large area of 50 km around the sites. The absolute number of buildings in a global area is likely to be more important than their precise local arrangement. A site located 200 meters away from a small village is not necessarily more threatened than a site located 20 km from a town of 50 000 habitants. Thus, patterns of variation between the two dates are not the same for P2 and P3. P3 is naturally less dispersed than P2 and stays localized in the same region at the two dates. The most impacted sites are those near existing areas of intense urbanization, *i.e.* in the lowland plains near the coast and in the Rhone valley. This explains the more important variation rates in terms of number of sites and species endangered compared to P2. Threatened sites in 2008 become more affected and spatially aggregated with additionally threatened sites with probably similar species community in 2030. This can also justify why birds represent the taxonomic group that is the most impacted in terms of number of species and number of sites per species. Indeed, in this region, many of the bird species of conservation interest occur in wetlands along the coast where urban development is currently higher and will thus be the most affected by future urbanization. Finally, the large-scale spatial effect of this pressure also explains the bigger surface area of sites. Indeed, within a 50 km radius, the size of the site is less important in determining the level of impact. At such scale, the pressure indicator refers to a wide range of indirect urbanization impacts caused by road traffic, water and air pollution and are therefore really difficult to predict and to limit. Special attention must be paid site per site in order to assess the potential threat in such sites.

Beyond the insights they provide into threat levels association with direct and indirect urban impacts on biodiversity, our use of pressure indicators has important implications for setting objective targets and for implementing conservation strategies (Margules and Pressey, 2000; Myers *et al.*, 2000; Pressey and Cowling, 2001). Here, a site based approach would recommend paying particular attention to sites with more than one pressure as a cumulative effect. We showed that in 2030, 192 sites will undergo at least two pressures, and 29 sites will undergo all three pressures. Species based information can also be useful for prioritization, since more attention should be paid to threatened species for which the region has a high responsibility; the French distribution of several plant species is for example limited to a small number of sites in the study region (Gauthier *et al.*, 2010). Particular attention must be given in order to assess the conservation interest of the 13 plants species predicted to be endangered by 2030 according to the three pressures.

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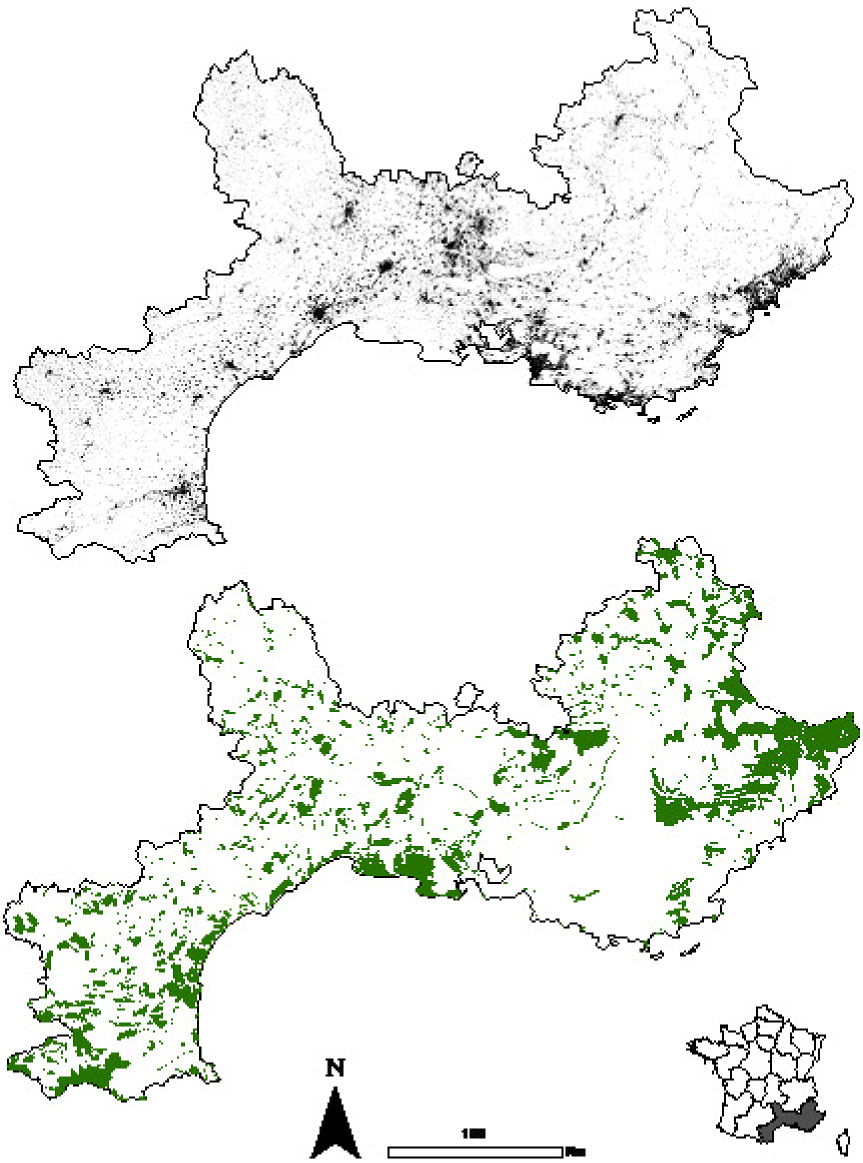

Figure 1 - The Mediterranean region of southern France with (a) the current distribution of urbanized areas and (b) the sites of high biodiversity interest (ZNIEFF inventory).

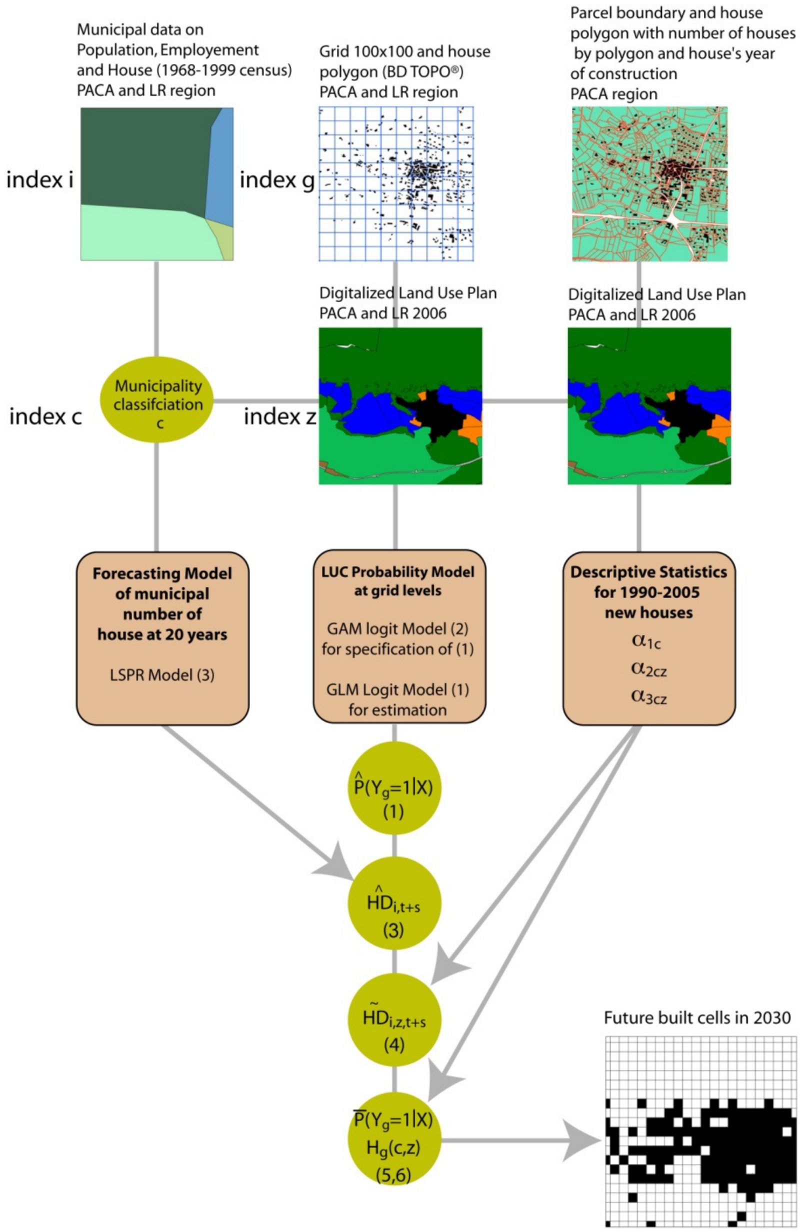

Figure 2 - Overview of the urban simulation model.

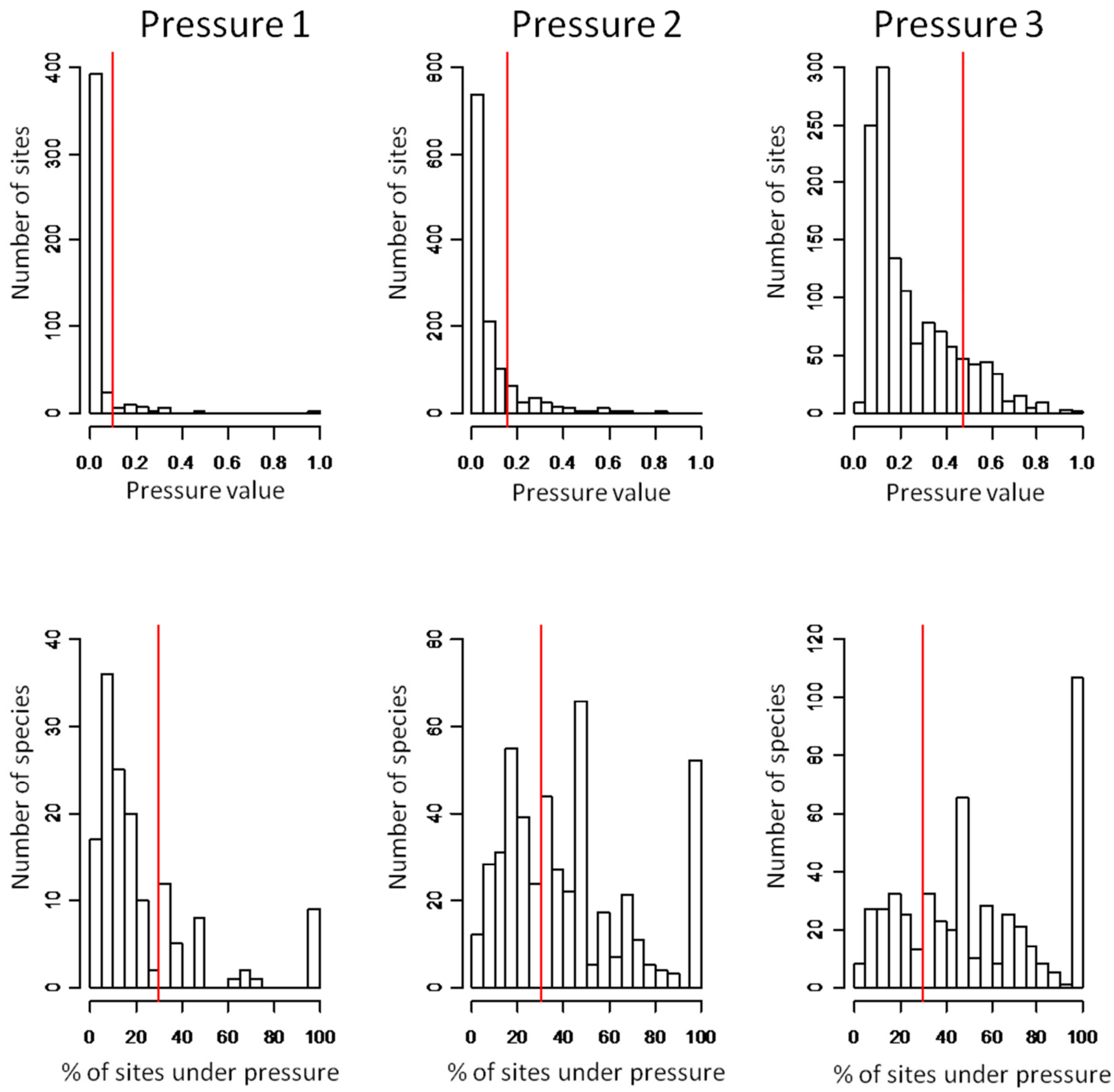

Figure 3 - Frequency distribution in 2030 of a) the pressure value on sites (when it is >0), b) the proportion of threatened sites per species (when it is >0) for each of the three pressure indicators. Vertical red lines represent the threshold values.

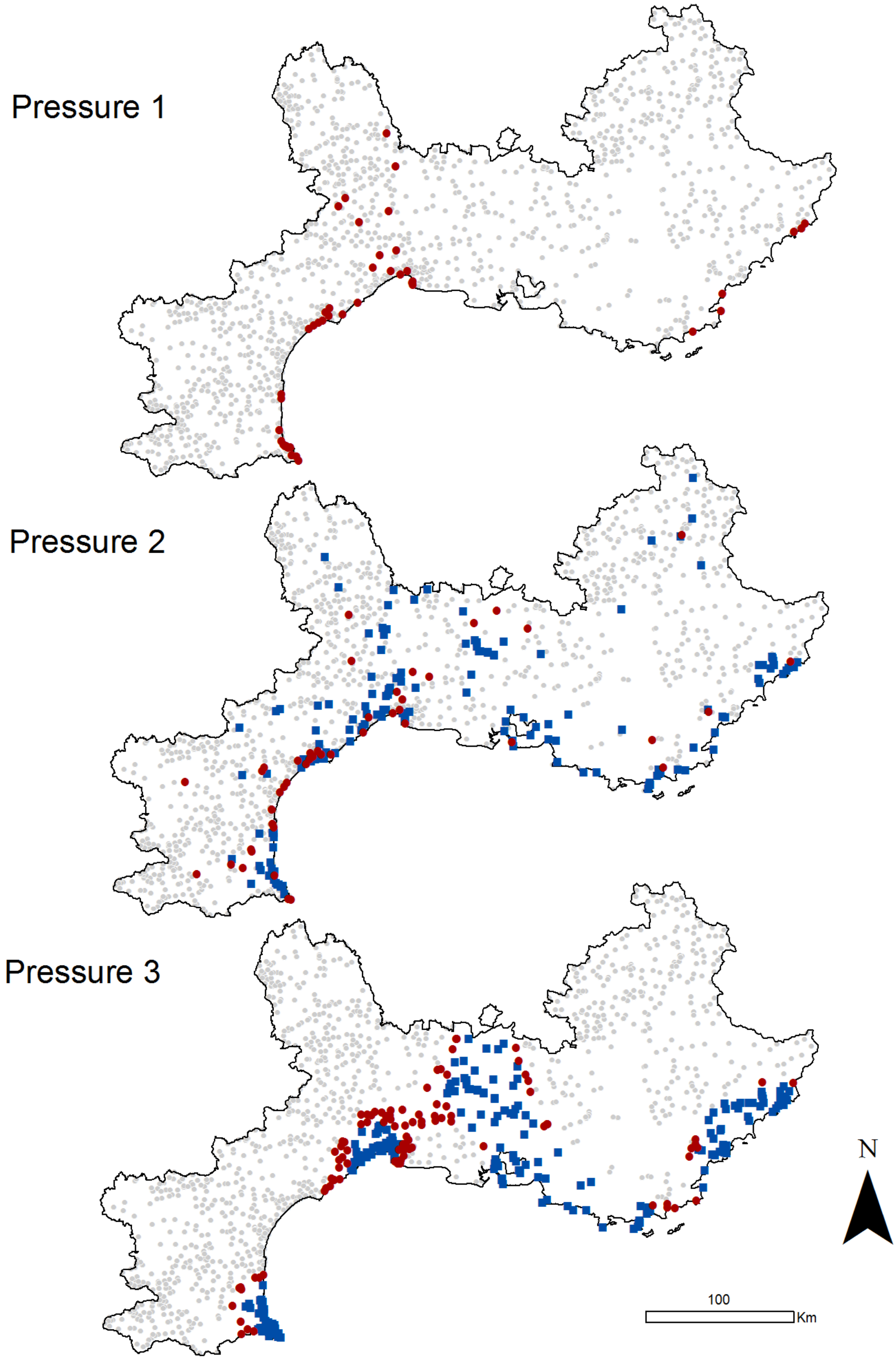

Figure 3 - Spatial distribution of threatened sites in relation to three pressure indicators. Blue squares refer to threatened sites in 2008; red points refer to the sites under pressure by 2030; grey points refer to the sites without pressure.