Article

Detecting and weighting the true corridors of species kinetics and gene flows: Linkage Flow Connectivity

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Abstract
Flow connectivity (FC) is a methodology, alternative and in opposition to both circuit theory and least-cost modelling, first introduced in 2013 to realistically forecast biotic flows over real landscapes. FC turns a static frictional map into a dynamical simulation of biotic flows from any source points indicated by the user. In this work, FC is further developed to find a solution to the problem of detecting the true corridors of species dispersals and gene flows. The output of this method is the realistic map of biotic corridors, determined in a bottom-up way by considering the interaction between landscape properties and species requirements, and not in a top-down approach based on the supposed expert knowledge of some researcher. Not only true corridors are mapped, but they are also automatically weighted based on their importance to support biotic flows. The same corridor can bear different levels of importance in different portions of its length. This outcome is pivotal from both conservation and management viewpoints. An applicative example is provided.

Keywords biotic shifts; dynamical GIS; flow connectivity; gene flow; landscape connectivity; landscape corridors; species dispersal; species conservation; species management.

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1 Introduction

Flow connectivity (FC hereafter) is a methodology introduced in 2013 (Ferrarini, 2013) to realistically forecast biotic flows and gene flows over real landscapes, conceptually and methodologically alternative and in opposition to both circuit theory (McRae, 2006; McRae and Beier, 2007; McRae et al., 2008) and least-cost modelling (Dijkstra, 1959).

Its name is due to the fact that it resembles the motion characteristic of fluids over a surface. In fact, FC relates biotic movements to fluid kinetics over the 3D frictional landscape built to represent species requirements. To do this, FC predicts species dispersal by minimizing at each time step the potential energy due to the fictional gravity force over the frictional 3D landscape built upon the real landscape. FC considers connectivity as a function of a continuous gradient of permeability values rather than attempting to distinguish discrete patches based on subjective thresholds of habitat area, quality or ownership. A theoretical and methodological comparison with circuit theory and least-cost modelling is discussed in Ferrarini (2013) and Ferrarini (2014d).

FC presents many variants (Table 1), each devoted to a particular topic of species dispersals over landscape. In this paper, I introduce a new variant called Linkage Flow Connectivity aimed to realistically individuate biotic corridors of species dispersals. Linkage FC adopts a bottom-up approach where corridors emerge from species-landscape interaction (as measured by frictional landscapes) and advanced modelling. Linkage FC opposes the idea that biotic corridors can a priori be individuated only by looking at the landcover map of a certain study area. This latter top-down approach is deemed anthropocentric, simplistic and unrealistic in FC.

Table 1 Flow Connectivity and its variants.

Name	Purpose	Year	Reference
Flow Connectivity	Predicting biotic flows over landscape	2013	Ferrarini 2013
Reverse Flow Connectivity	Assigning true-to-life friction values to biotic flows	2014	Ferrarini 2014
Backward Flow Connectivity	Tracing biotic dispersals back in time	2014	Ferrarini 2014b
Sloping Flow Connectivity	Detecting barriers and facilities to species dispersal	2014	Ferrarini 2014c
Bottleneck Flow Connectivity	Detecting landscape bottlenecks of species dispersal	2015	Ferrarini 2015
Climatic Flow Connectivity	Incorporating climatic change into biotic connectivity	2015	Ferrarini 2015b
What-if Flow Connectivity	Integrating landscape changes into biotic connectivity	2015	Ferrarini 2015c
Momentum Flow Connectivity	Mapping landscape impulses to species dispersal	2015	Ferrarini 2015d
Stochastic Flow Connectivity	Associating uncertainty to biotic flows prediction	2016	Ferrarini 2016
Linkage Flow Connectivity	Detecting the true corridors of species dispersals	2016	this work

2 Linkage Flow Connectivity: Mathematical Formulation

2.1 Opening definitions

Let $L(x,y,z,t)$ be a real 3D landscape at generic time *t*, where $L \in [1,...,n]$. *L* is thence a generic (categorical) landcover (or land-use) map with *n* classes.

At time $T_{0,}$

$$L_0 = L(x,y,z,t_0) \quad (1)$$

Let $\varphi(L)$ be the landscape friction (i.e. how much each land parcel is unfavorable) to the species under study.

Differently stated, $\varphi(L)$ is a function that associates a friction value to each pixel of *L*.

Landscape friction $\varphi(L)$ has 2 components (structural and functional) and the overall friction should be equal to their product since they're interactive:

$$\varphi(L) = \varphi_{STR}(L) * \varphi_{FUNC}(L) \tag{2}$$

At time T_0,

$$\varphi_0 = \varphi(L_0) \tag{3}$$

True-to-life coefficients for $\varphi(L)$ can be calculated in flow connectivity as depicted in Ferrarini (2014). Alternatively, a simpler solution used by FC to the assessment of realistic friction coefficients is the application of suitability modelling to the detected points of species presence over the landscape. In particular, MAXENT methodology (Phillips et al., 2006) is particularly well suited to determine suitability maps starting from points of species presence. MAXENT computes the suitability scores $\mu(L)$ for each portion of the landscape in the 0-100 range. Thus, friction coefficients can be properly calculated in FC as the complementary to 100 of suitability:

$$\varphi(L) = 100 - \mu(L) \tag{4}$$

Let $L_s(x, y, \varphi(L))$ be a landscape where, for each pixel, the *z*-value is equal to the friction for the species under study. In other words, L_s is a 3D fictional landscape with the same coordinates and geographic projection as L, but with pixel-by-pixel friction values in place of real *z*-values. Higher elevations represents areas with elevated friction to the species due to whatever reason (unsuitable landcover, human disturbance etc), instead lower altitudes represent the opposite. At time T_0,

$$L_{s0} = L_s(x, y, \varphi(L_0)) \tag{5}$$

Let $S(x, y, t)$ be a binary landscape (of which S_{xyt} represents the value of the generic pixel at time t) with the same coordinates and geographic projection as L_s and L, but with binary values at each pixel representing species presence/absence at generic time t. At time T_0,

$$S_0 = S(x, y, t_0) \tag{6}$$

Species presence is hence given by $S_0 = 1$, while species absence by $S_0 = 0$.

2.2 Corridor detection

Three steps are required to properly detect corridors of biotic shifts over the true landscape $L(x, y, z, t)$:

- to initiate n starting points $S_0 = 1$ uniformly distributed on $L_s(x, y, \varphi(L))$;
- to simulate the biotic shift from each starting point;
- for each landscape pixel, to count how many times biotic shifts flow though such pixel.

The governing equation of biotic flows over the frictional landscape L_s is as follows (Ferrarini, 2013)

$$\frac{\delta S(x, y, t)}{\delta t} = \text{div } S = \nabla \cdot S = \frac{\delta S}{\delta x} + \frac{\delta S}{\delta y} \tag{7}$$

with initial conditions S_0 at time T_0. The symbol δ is a notation for a differential (i.e. ∂) or a difference (i.e. Δ) partial equation depending on the kind of landscape under study. For a high-resolution frictional landscape it represents a differential operator that simulates almost continuous movements over such landscape, conversely for a low resolution landscape it describes discrete movements both in space and time.

As showed in Ferrarini (2013), the biotic flow of Eq. 7 can be solved using the kinetic equation

$$\frac{\delta S}{\delta t} = \begin{cases} 0 \quad if \quad \dfrac{\delta S}{\delta x} = \dfrac{\delta S}{\delta y} = 0 \\ 1 \quad if \quad (\dfrac{\delta S}{\delta x} = 1 \; and \; \dfrac{\delta S}{\delta y} = 0) \\ \qquad or \; (\dfrac{\delta S}{\delta x} = 0 \; and \; \dfrac{\delta S}{\delta y} = 1) \\ \qquad or \; \dfrac{\delta S}{\delta x} = \dfrac{\delta S}{\delta y} = 1 \end{cases} \tag{8}$$

FC assumes that the species dispersal ends at a stability point, if exists, where:

$$\frac{\delta S(x,y,t)}{\delta t} = \nabla \cdot S = 0 \tag{9}$$

In other words, a stability point exists when one species finds itself in a portion of the frictional landscape where all the surrounding pixels have equal or higher frictional values. When this happens, FC assumes that the study species has no reasons to move further.

Eqs. 8 and 9 are calculated for each of the *n* starting points required by Linkage FC. Then, in order to count how many biotic shifts passed though each pixel, Linkage FC makes use of the following equation

$$C_w = \int_{t=0}^{t=eq} \frac{\delta S(x,y,t)}{\delta t} \, dt = \int_{t=0}^{t=eq} \nabla \cdot S \; dt \tag{10}$$

It's clear that C_w is a counter activated for each pixel that sums 1 each time that such pixel is crossed by one out of the *n* simulated biotic shifts from time $T=0$ up to the equilibrium time (i.e. when all shifts reached their stability points).

In order to count the total flow F_T over all the landscape pixels due to the *n* biotic shifts, Linkage FC makes use of the following equation

$$F_T = \int_{L(x,y,\varphi(L))} \left(\int_{t=0}^{t=eq} \frac{\delta S(x,y,t)}{\delta t} dt \right) dxdy = \int_{L(x,y,\varphi(L))} \left(\int_{t=0}^{t=eq} \nabla \cdot S \; dt \right) dxdy \tag{11}$$

It's clear that F_T counts the number of biotic passages through all the landscape pixels from time $T=0$ up to the equilibrium time. This represents the overall amount of movements from the *n* starting points. It can be easily conceived as a "volume" of movements on the 2D (i.e *xy*) landscape, where time represents the third dimension (i.e. *z*). In order to apply Linkage FC modelling to real landscapes, I wrote the *ad hoc* software Connectivity Lab (Ferrarini, 2013b).

3 An Applicative Example

The Ceno valley is a 35,038 ha wide valley situated in the Province of Parma, Northern Italy. It has been mapped at 1:25,000 scale (Ferrarini, 2005; Ferrarini et al., 2010) using the CORINE Biotopes classification system. The landscape structure of the Ceno Valley has been widely analyzed (Ferrarini and Tomaselli, 2010; Ferrarini, 2011; Ferrarini, 2012; Ferrarini, 2012b).

Several wolf populations have been recently observed *in situ* by life-watchers, environmental associations and local administrations. I have applied Linkage FC to a portion of the Ceno valley above 1000 m a.s.l. close to the municipality of Bardi (Fig. 1). The area is a square of about 20 km * 20 km. Optimized friction values $\varphi(L)$ to wolf presence are borrowed from Ferrarini (2012c).

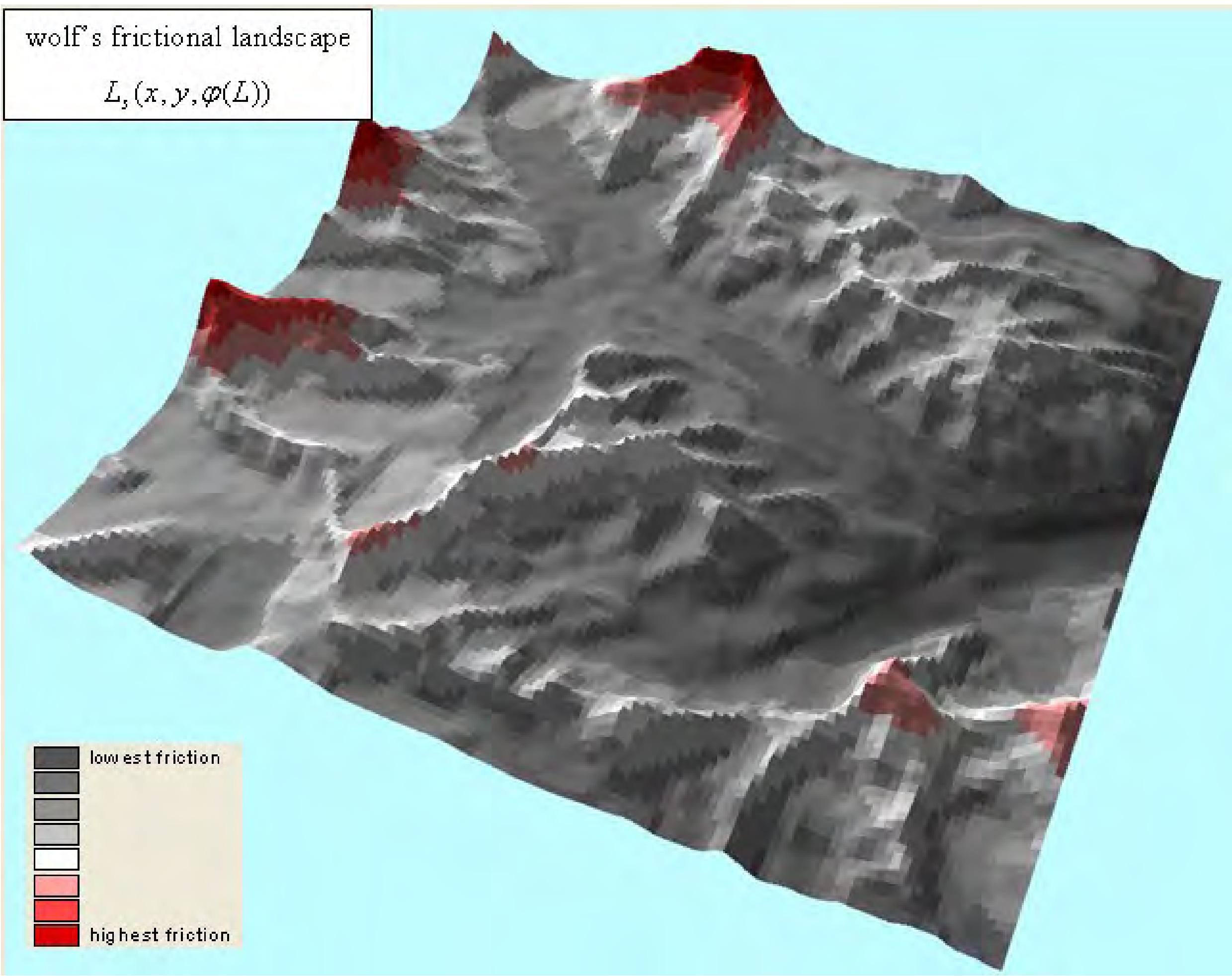

Fig. 1 The frictional landscape $L_s(x, y, \varphi(L))$ has been built for wolf upon a portion (20 km * 20 km) of the Ceno valley (province of Parma, Italy) that represents here the real landscape *L(x,y,z,t)*. The elevation represents for each pixel the landscape friction $\varphi(L)$ for the species under study: the higher the elevation, the higher the friction to the species. Linear ridges mainly represent the friction due to roadways.

Linkage FC used here 200 starting points (Fig. 2), thus 200 wolf's shifts were simulated using Flow Connectivity's kinetic equation (i.e. Eq. 8). After that all shifts reached an equilibrium point (Eq. 9), Linkage Flow Connectivity counted the number of wolf's passages through each pixel (Eq. 10). Linkage Flow Connectivity also counted the total volume of wolf's movements over the 20 km * 20 km study area using Eq. 11.

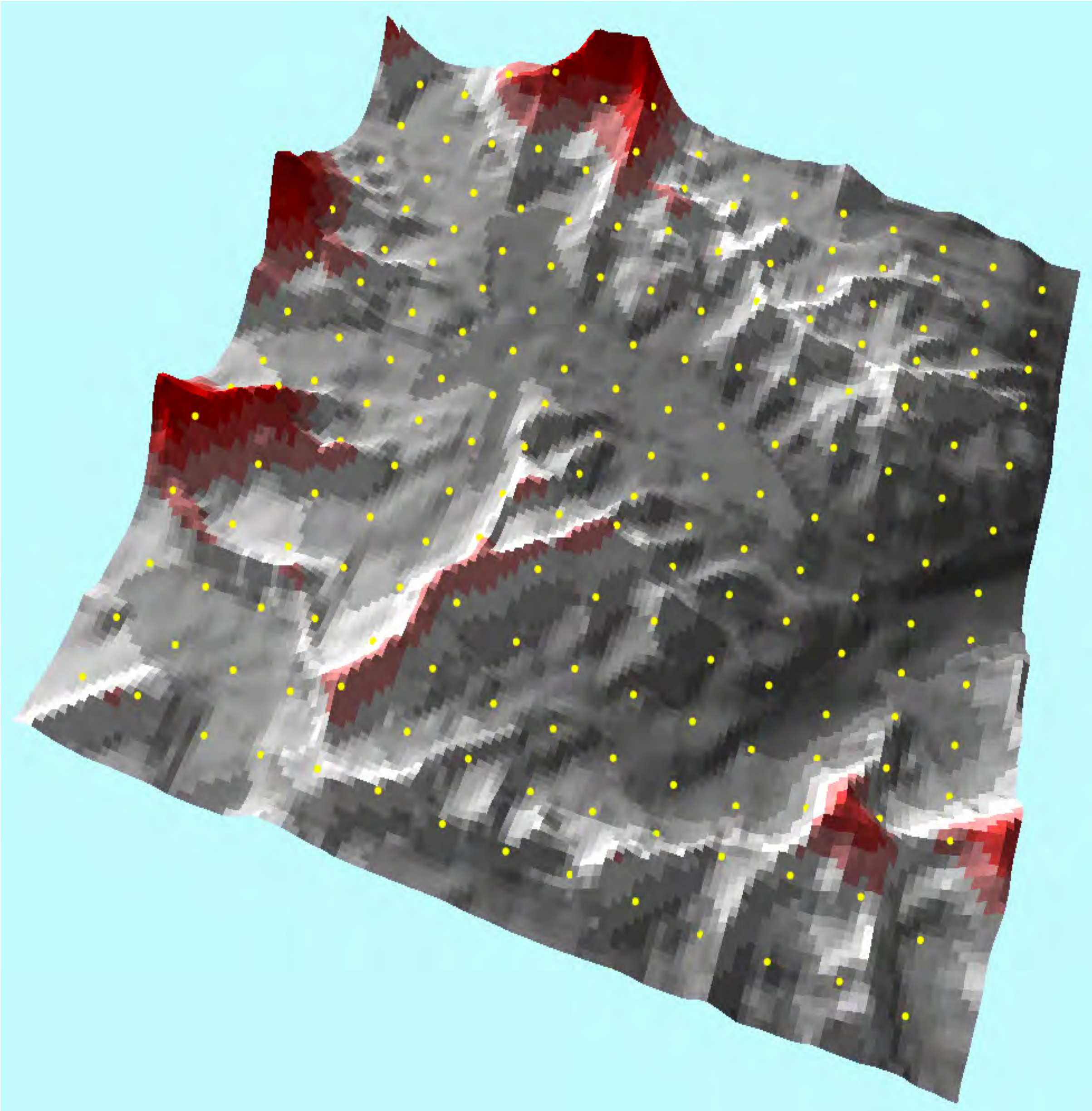

Fig. 2 In yellow, 200 simulated starting points over the frictional landscape of Fig. 1.

On average, each landscape pixel has been used 21.4 times (±95 Std. Dev.) during the overall 343,551 wolf's movements (Eq. 11) of the 200 simulations. The most used pixel scored 1867 biotic passages. If we only consider landscape pixels with at least one wolf's passage, the average number of passages has been 31.83 (±112 Std. Dev.). In total, 228.6 km of corridors have been detected (Fig. 3).

The average C_w of corridors was 185.85 (i.e. Linkage FC counted on average about 186 passages through a generic landscape pixel belonging to corridors), with minimum value equal to 8.61. The dendritic nature of biotic corridors is evident and it is the obvious result of the theoretical and algorithmic nature of Flow Connectivity that relates biotic movements to fluid kinetics over the frictional 3D landscape built to represent species requirements (Fig. 4).

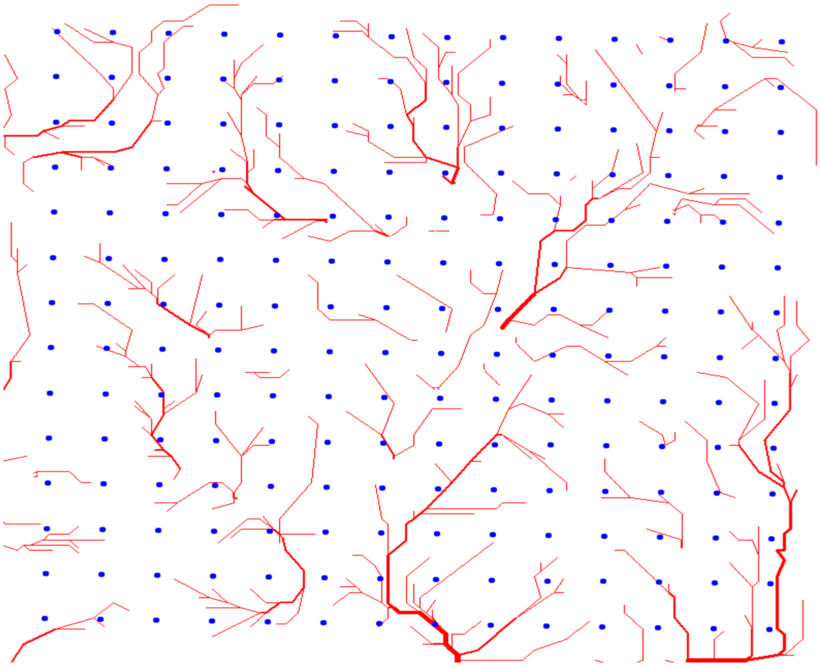

Fig. 3 Application of Linkage Flow Connectivity to the 20 km * 20 km study area in the Ceno valley. In blue, 200 simulated starting points. In red, the detected corridors. Thicker lines indicates a more elevated value of C_w. The dendritic nature of biotic corridors is evident. In total, 228.6 km of corridors have been detected.

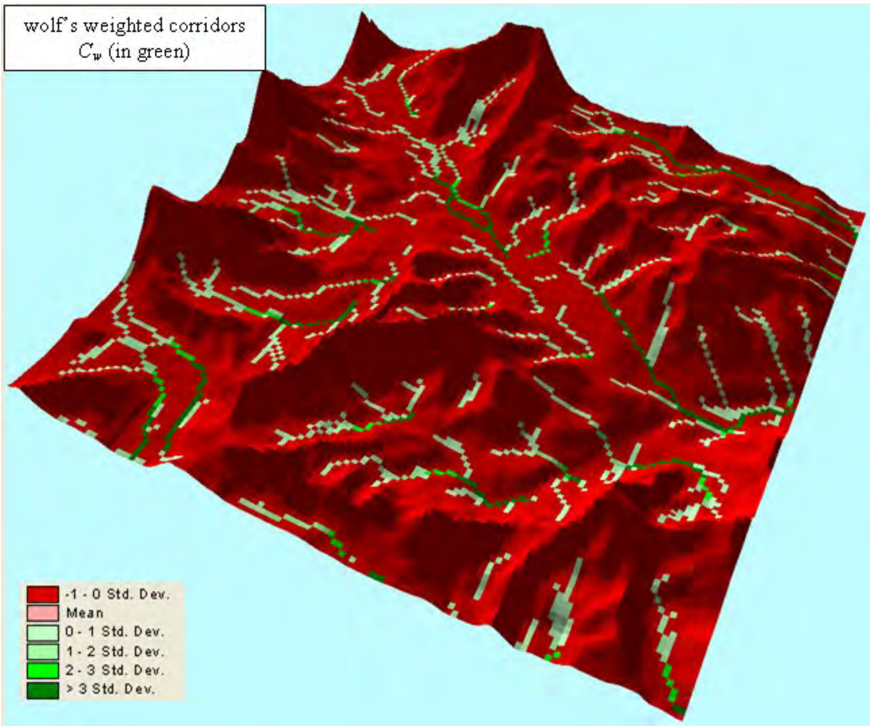

Fig. 4 3D representation of the detected corridors. Corridors are in different levels of green depending on the degree of biotic flow C_w. Red areas are partially or totally unsuitable areas for biotic flows. In total, 228.6 km of corridors have been detected.

4 Conclusions

The detection of the true corridors of biotic kinetics and gene flows is a pivotal task for species and genetic conservation and management.

Linkage Flow Connectivity adopts a bottom-up approach where corridors emerge from species-landscape interaction (as measured by frictional landscapes) and advanced modelling. Linkage FC opposes the idea that biotic corridors can be individuated by researchers only looking at the landcover map of a certain study area. This latter top-down approach is deemed anthropocentric, simplistic and unrealistic. Instead realism is, and should be, the first and primary goal of any modelling and simulative framework.

The outputs of Linkage Flow Connectivity are polyline vector maps (in both *.shp* and *.kml* formats) of corridors with the associated value of C_w to represent the degree of importance of each corridor. Such polyline maps can be easily superimposed to digital orthophotos, technical maps and GoogleEarth images.

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