Article

Mapping landscape impulses to species dispersal: Momentum flow connectivity

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Abstract

Species dispersal over the landscape is a dynamical issue. By the way, such biotic process is promoted by a static process, i.e. how much each portion of the landscape pushes species dispersal, and towards which directions. In this view, in this paper I add a further skill to Flow Connectivity, i.e. the potential of calculating and mapping the azimuthal impulses of the landscape to biotic flows. Momentum Flow Connectivity is able to produce landscape maps (both vectorial and raster) of impulse strengths and directions to biotic dispersal. The contribution of this new tool to the conservation of priority species and to the eradication of undesired exotic ones is obvious.

Keywords biotic flows; dynamical GIS; flow connectivity; gene flow; impulse map; landscape momentum; partial differential equations; species dispersal; vector calculus.

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1 Introduction

Flow connectivity (FC; Ferrarini 2013; Ferrarini 2014; Ferrarini 2014b; Ferrarini 2014c; Ferrarini 2014d; Ferrarini 2015; Ferrarini 2015b; Ferrarini 2015c) has been recently introduced as a modelling approach to properly simulate biotic movements over real landscapes.

In this paper, I add a new skill to FC called “Momentum Flow Connectivity” (MFC). The term “momentum” stands here for the azimuthal impulses to biotic movements provided by the actual landscape to the species under study. The goal of this proposal is to answer a nontrivial question: given a generic point of the landscape, where will the study species will be pushed on from such point, and with how much strength?

2 Momentum Flow Connectivity: Mathematical Formulation

Let $L(x,y,z,t)$ be a real 3D landscape at generic time *t*, where $L \in [1,...,n]$. Thus, *L* is a generic (categorical) landcover (or land-use map) with *n* classes. Let $\varphi(L)$ be the landscape friction (i.e. how much each land parcel is unfavorable) to the species under study. In other words, $\varphi(L)$ is a function that associates a friction value to each pixel of *L*. 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. L_s is hence 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 some reason (unsuitable landcover, human disturbance etc), while lower altitudes represent the opposite.

True-to-life coefficients for landscape friction $\varphi(L)$ can be calculated as in Ferrarini (2014b), where I defined *P* as the predicted path for the species over the fictional landscape L_s, and P^* the real path followed by the species as detected by GPS data-loggers or *in situ* observations. The bias *B* between *P* and *P** can be calculated as

$$B = \text{mod}(\int Pdx - \int P^* dx) \tag{1}$$

where the function *mod* indicates the module of the difference between the two integrals, while *x* is the map longitude. Hence:

$$B = \begin{cases} \int Pdx - \int P^* dx & \text{where } P > P^* \\ \int P^* dx - \int Pdx & \text{where } P^* > P \end{cases} \tag{2}$$

Now, true-to-life coefficients for landscape friction $\varphi(L)$ are calculated by optimizing *B* as

set B to 0 (3)

or, at least,

minimize B (4)

The optimization of $\varphi(L)$ can be properly achieved using genetic algorithms (GA; Holland, 1975). GA are powerful evolutionary models with wide potential applications in ecology and biology, such as optimization of protected areas (Ferrarini et al., 2008; Parolo et al., 2009), optimal sampling (Ferrarini, 2012a; Ferrarini, 2012b), optimal detection of landscape units (Rossi et al., 2014) and networks control (Ferrarini, 2011a; Ferrarini, 2011b; Ferrarini, 2013b; Ferrarini, 2013c; Ferrarini, 2013d; Ferrarini, 2013e; Ferrarini, 2014e; Ferrarini, 2015d; Ferrarini, 2015e).

MFC acts upon the optimized frictional landscape $L_s(x,y,\varphi(L))$ by calculating the module *M* of the momentum as the derivatives of the 3D frictional surface using centered finite differences (Burrough and McDonnell, 1998):

$$M = \sqrt{\frac{\delta^2 L_s(x,y,\varphi(L_0))}{\delta^2 x} + \frac{\delta^2 L_s(x,y,\varphi(L_0))}{\delta^2 y}} \tag{5}$$

The symbol δ is a notation for a differential (i.e. ∂) or a difference (i.e. Δ) partial equation depending on the spatial resolution of the landscape under study. In other words, *M* represents the pixel-by-pixel impulse of the frictional landscape calculated as a percentage. The higher *M*, the more elevated the impulse to the biotic movement imposed to the species by the actual landscape. *M* can also be measured in degrees (i.e. 0-90°) by MFC using the alternative equation:

$$M_{\deg} = \arctan(\sqrt{\frac{\delta^2 L_s(x,y,\varphi(L_0))}{\delta^2 x} + \frac{\delta^2 L_s(x,y,\varphi(L_0))}{\delta^2 y}}) * \frac{180}{\pi} \tag{6}$$

To calculate the orientation of landscape momentum (i.e., the direction in which the species is pushed toward), MFC makes use of the equation by Evans (1972)

$$M_{or} = \arctan\left(-\frac{\dfrac{\delta L_s(x,y,\varphi(L_0))}{\delta y}}{\dfrac{\delta L_s(x,y,\varphi(L_0))}{\delta x}} \right) \tag{7}$$

which is the angle by the *x* and *y* derivative of L_s via *arctan*, measured clockwise in degrees from North. Hence, *M* and M_{or} are respectively the module and the direction of the momentum vector which acts at each landscape pixel.

In order to apply MFC modelling to real landscapes, I wrote the *ad hoc* software Connectivity-Lab (Ferrarini, 2013f).

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 deeply analyzed (Ferrarini, 2005b; Ferrarini and Tomaselli, 2010; Ferrarini, 2011c; Ferrarini, 2012c; Ferrarini, 2012d). Recently, the shift of wolf populations from the montane belt to the lowland has been registered. Several populations have been observed *in situ* by life-watchers, stakeholders, environmental associations and local administrations.

I have applied MFC to a portion of the Ceno valley (Fig. 1) above 1000 m a.s.l. close to the municipality of Bardi where several small populations of wolves have been observed. The area corresponds to a square of about 12 km * 12 km. Optimized friction values $\varphi(L)$ to wolf presence are borrowed from Ferrarini (2012e) in the form of friction coefficients assigned to every land cover classes.

The application of equations from (5) to (7) provided the results showed in Fig. 2 and Fig. 3. The impulse map of Fig. 2 has been generated through the Connectivity-Lab software by placing sampling points separated by 1 km both in latitude and longitude. Then MFC has been applied to the resulting points, each one representing the start point of the impulse vector.

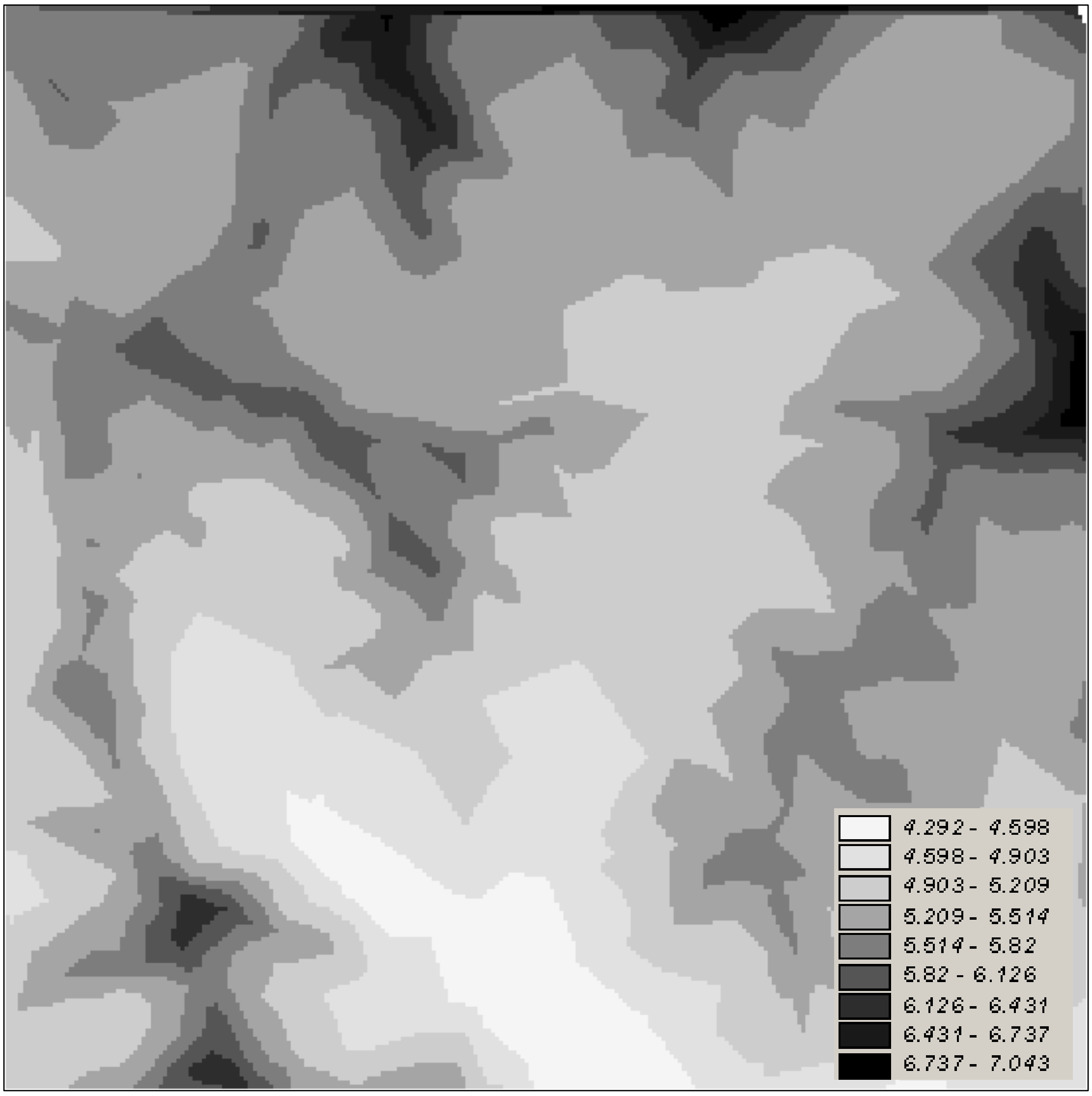


Fig. 1 The frictional landscape *Ls* built for wolf upon a 12 km * 12 km portion of the Ceno Valley (province of Parma, Italy). It represents here the real landscape *L(x,y,z,t)*. The higher frictional values are in dark grey, the lower ones are in white.

Fig. 2 clearly depicts how the study area pushes wolf's dispersal. The length of each impulse vector is proportional to the impulse strength (i.e., Eq. 5), so it clearly emerges the predominance of Southern and Eastern impulses, both for the number of impulse vectors and their strengths. The impulse map of Fig. 3 has been generated through the Connectivity-Lab software by placing sampling points separated by 500 m both in latitude and longitude. Then MFC has been applied to the resulting points, each representing the origin of the impulse vector.

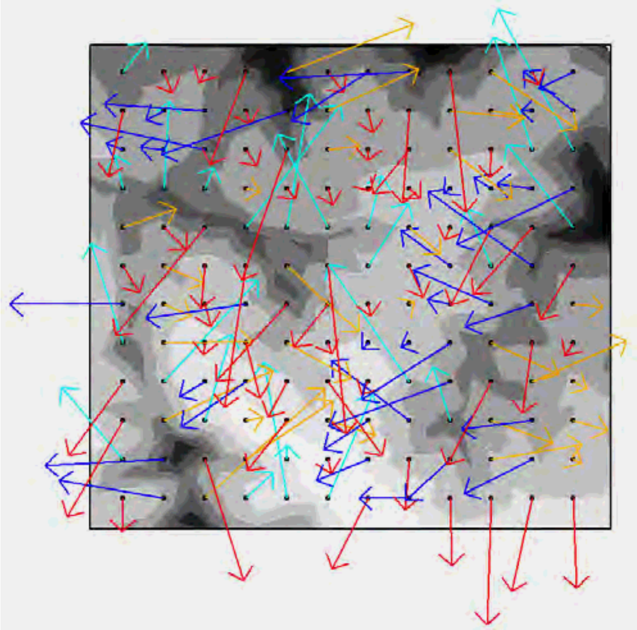


Fig. 2 Impulse map calculated by Momentum Flow Connectivity upon the frictional landscape of Fig. 1 with 144 sampling points separated by 1 km both in latitude and longitude. Each arrow indicates the magnitude (calculated via Eq. 5) and the direction (calculated via Eq. 7) of the azimuthal impulses (dynamic imprints) of the frictional landscape to species dispersal. The arrow colours group the flow directions into 4 categories: North (cyan arrows), East (orange arrows), South (red arrows) and West (blue arrows).

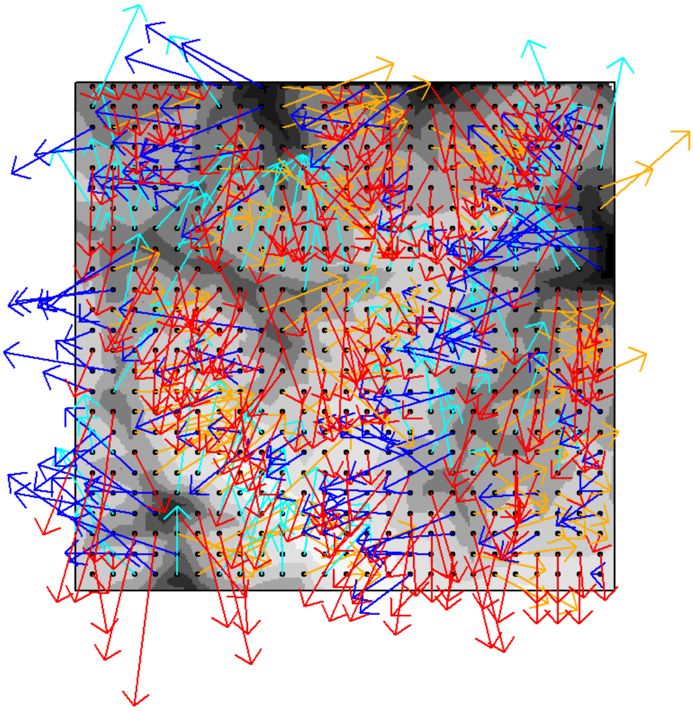


Fig. 3 Impulse map generated by Momentum Flow Connectivity upon the frictional landscape of Fig. 1 with 625 sampling points separated by 500 meters both in latitude and longitude. Each arrow indicates the magnitude (calculated via Eq. 5) and the direction (calculated via Eq. 7) of the azimuthal impulses (dynamic imprints) of the frictional landscape to species dispersal. The arrow colours group the flow directions into 4 categories: North (cyan arrows), East (orange arrows), South (red arrows) and West (blue arrows).

Fig. 3 confirms and deepens the output of Fig. 2 about how the study area pushes wolf’s dispersal. The predominance of Southern and Eastern impulses, both for the number of impulse vectors and their strengths, results confirmed. These cartographic outputs can then be summarized by the numeric results produced by Connectivity-Lab along with the cartographic ones, so they can be further analyzed using basic circular statistics (Fig. 4 and Tab. 1).

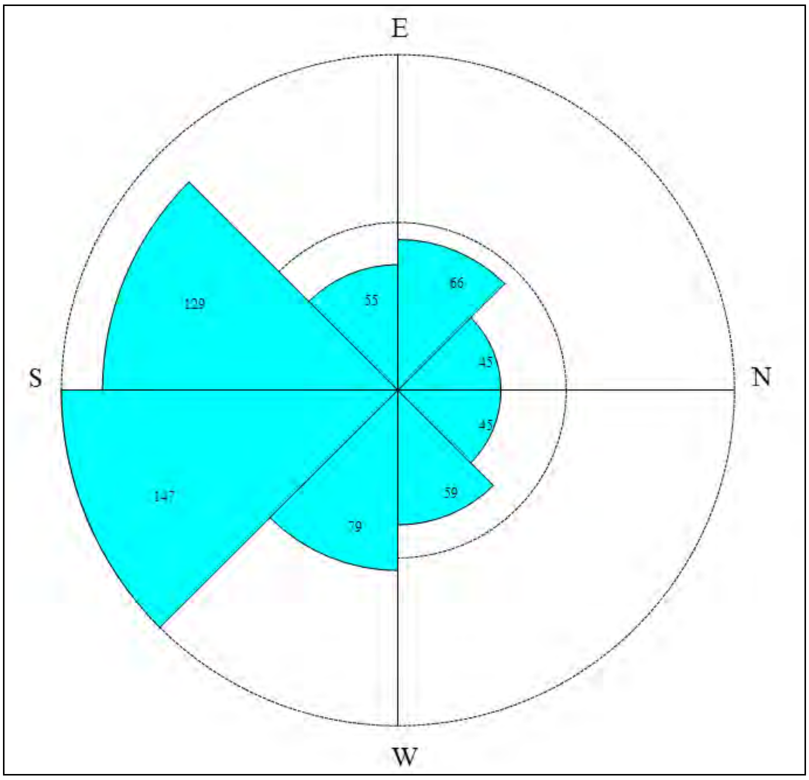
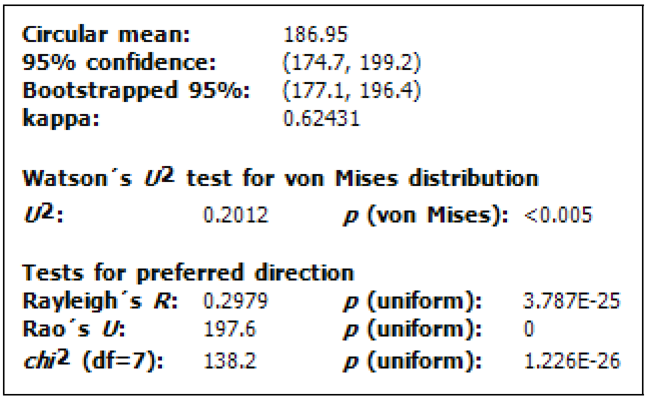


Fig. 4 Circular diagram of the azimuthal impulses of the study landscape of Fig. 1 upon the wolf species for the 625 vectors of Fig. 3. There are 8 sectors corresponding to the 8 cardinal directions. It results clear that the species under study is mainly pushed by the actual landscape towards SE (147 times out of 625) and SO directions (129 times out of 625) while Northward impulses (NE and NO) are very infrequent.

Table 1 Circular statistics of the azimuthal impulses of the study landscape of Fig. 1 upon the wolf species for the 625 vectors of Fig. 3. The circular mean (186.95°) almost perfectly corresponds to the South direction (i.e., 180°). The landscape momentum for the species does not follow von Mises distribution (rejection of the Von Mises distribution hypothesis) and is not uniformly distributed (rejection of the preferred direction hypothesis).



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Circular mean:        186.95
95% confidence:       (174.7, 199.2)
Bootstrapped 95%:     (177.1, 196.4)
kappa:                0.62431

Watson´s U2 test for von Mises distribution
U2:              0.2012        p (von Mises):  <0.005

Tests for preferred direction
Rayleigh´s R:    0.2979        p (uniform):      3.787E-25
Rao´s U:         197.6         p (uniform):      0
chi2 (df=7):     138.2         p (uniform):      1.226E-26
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4 Conclusions

The conservation of species of interest and the eradication of undesired exotic species both require advanced methodological tools on top of realistically simulating what happens in the real world landscapes.

While Flow connectivity produces dynamical simulations within GIS, Momentum Flow Connectivity creates static GIS layers (both vectorial and raster) that represent landscape impulses to species dispersal. The conjoint use of these tools provides firm scientific bases on which proper conservation management and planning can be realized.

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