

Article

## Detecting barriers and facilities to species dispersal: Introducing sloping flow connectivity

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### Abstract

Connectivity in ecology deals with the problem of how biotic dispersals can happen, given actual landscape properties and species presence/absence over such landscape. Recently I have introduced a modelling approach (flow connectivity) to ecological connectivity that is alternative to circuit theory, and is able to fix the weak point of the “from-to” connectivity approach. In addition, I’ve introduced “reverse flow connectivity” that couples evolutionary algorithms to partial differential equations in order to fix the problem of subjectivity in the attribution of friction values to landscape categories. I’ve also showed that flow connectivity can be used to predict biotic movements happened in the past (backward flow connectivity). To date, there has been little effort by conservation scientists towards detecting restoration opportunities by mapping barriers that strongly reduce movement potential. In this paper, I introduce a new kind of theoretical and modelling approach called “sloping flow connectivity”. The goal of such proposal is to individuate and map barriers and facilities to species dispersals over the landscape. I define here a barrier as a landscape feature that impedes biotic movements, the removal of which would increase the potential for biotic shifts. Using sloping flow connectivity, it’s possible to plan greenways and ecological networks in an effective manner, since it is able to enhance the real potential of each landscape elements to facilitate or obstruct both directional and overall species movements.

**Keywords** biotic flows; dispersal facilities; flow connectivity; gene flow; landscape barriers; landscape connectivity; partial differential equations; species dispersal.

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### 1 Introduction

Predicting how animals disperse is a pivotal issue for the management and conservation of fragmented populations. Landscape heterogeneity and fragmentation affect how organisms are distributed in the landscape (Fahrig and Merriam, 1985; Kennedy and Gray, 1997), determine the chance of a patch being colonized (Hanski and Ovaskainen, 2000), reduce inbreeding in small populations and maintains evolutionary potential

(Couvet, 2002). In order to predict dispersal, it is important to not only consider an organism's dispersal capabilities, but also the complex interactions between its behaviour and the landscape pattern and use.

The modelling of animal dispersal provides a useful tool for investigating these complex interactions, and it is an essential goal for biotic conservation planning (Kareiva and Wennergren, 1995; King and With, 2002). Due to the difficulty in gathering experimental results on species dispersal, simulation models have become a cost-effective approach to predict dispersal dynamics (Tischendorf, 1997; Wiegand et al., 1999; Tischendorf and Fahrig, 2000). Simulation models with spatially-explicit landscapes enable the integration of the relationships between species and the landscape, and provide representation of the spatial elements that promote or constrain dispersal. Several dispersal models with spatially explicit landscapes have been developed. Some consider dispersal behaviour according to habitat affinity or physiological states in order to predict animal movements and provide guidelines for landscape and wildlife management (Gustafson and Gardner, 1996; With et al., 1997; Gardner and Gustafson, 2004).

Recently I have introduced a modelling approach (flow connectivity; Ferrarini, 2013a) to ecological connectivity that is alternative to circuit theory (McRae, 2006; McRae and Beier, 2007; McRae et al., 2008), and is able to fix the weak point of the "from-to" connectivity approach. Landscape connectivity as estimated by circuit theory relies on a strong assumption that is possibly untrue, unproven or very challenging to be demonstrated: species dispersals are "from-to" movements, i.e. from source points (patches) of the landscape to sink ones. Source and sinks are suitable areas present within a matrix that is partially or completely hostile to the species. There are two aspects of this approach that are questionable. First, a source-sink habitats model can be suitable to describe lowland landscapes where few suitable patches (e.g. protected areas) are surrounded by a dominant, hostile (or semi-hostile) anthropogenic landscape. By the way, can we think the same of mountain and hilly landscapes? Such landscapes are not composed of source and sink habitats, instead they're a continuum with a natural matrix where the source-sink habitats model loses its rationale. Second, assuming that a species aims to go from "patch A" to "patch B" means that such species is supposed to plan such dispersal path (i.e. global optimization). This could be true for short-range dispersals where the final point is visible from the starting one, but for wide-range movements, and for plant species in particular, the dispersal model postulated by circuit theory is unsuitable.

In addition, I've introduced "reverse flow connectivity" (Ferrarini, 2014a) that couples evolutionary algorithms to partial differential equations in order to fix the problem of subjectivity in the attribution of friction values to landscape categories. I've also showed that flow connectivity can be used to predict biotic movements happened in the past (backward flow connectivity; Ferrarini, 2014b).

In this paper, I introduce a new kind of theoretical and modelling approach called "sloping flow connectivity". The goal of such proposal is to individuate barriers (to be removed) and facilities (to be conserved) to species dispersal over the landscape. The reason behind sloping flow connectivity is that it makes possible to plan greenways and ecological networks in an effective manner, since it is able to enhance the real potential of each landscape elements to facilitate or obstruct directional and overall species movements.

## 2 Sloping Flow Connectivity: Mathematical Formulation

Let  $L(x, y, z, t)$  be a real 3D landscape at generic time  $t$ , where  $L \in [1, \dots, n]$ . In other words,  $L$  is 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 unfavourable) to the species under study. In other words,  $\varphi(L)$  is a function that associates a friction value to each pixel of  $L$ . At time  $T_0$ ,

$$\varphi_0 = \varphi(L_0) \tag{2}$$

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), while lower altitudes represent the opposite.

True-to-life coefficients for landscape friction can be calculated as in Ferrarini (2014a), 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  $P^*$  is hence calculated as

$$B = \text{mod}(\int P dx - \int P^* dx) \tag{3}$$

where the function *mod* indicates the module of the difference.

Hence:

$$B = \begin{cases} \int P dx - \int P^* dx & \text{where } P > P^* \\ \int P^* dx - \int P dx & \text{where } P^* > P \end{cases} \tag{4}$$

Now, true-to-life coefficients for landscape friction can be calculated by optimizing  $B$ , as follows:

$$\text{set } B \text{ to } 0 \tag{5}$$

or, at least,

$$\text{minimize } B \tag{6}$$

The optimization of  $\varphi(L)$  can be properly achieved using genetic algorithms (GAs; Holland, 1975). GAs 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, 2013b; Ferrarini, 2013c; Ferrarini, 2013d; Ferrarini, 2013e; Ferrarini, 2014c). At time  $T_0$ ,

$$L_{s0} = L_s(x, y, \varphi(L_0)) \tag{7}$$

Now, sloping flow connectivity acts upon the optimized frictional landscape of eq. (7) as follows:

$$\frac{\delta L_s(x, y, \varphi(L_0))}{\delta \vec{v}(x, y)} \tag{8}$$

In other words, sloping flow connectivity calculates (pixel-by-pixel) the slope of the optimized frictional landscape along the (vectorial) direction  $v$  that is a function of  $x$  and  $y$  dimensions:

$$\vec{v} = a\hat{x} + b\hat{y} \tag{9}$$

For instance, with  $a=0$  and  $b=1$  eq (8) calculates the frictional slope toward the N direction; with  $a=1$  and  $b=1$ , eq. (8) calculates the frictional slope toward the N-E direction. Since  $a$  and  $b$  are real numbers, sloping connectivity is able to calculate slope not only along the 8 cardinal directions (N, E, S, O, N-E, S-E, N-O, S-O), but along any compass bearing.

In order to estimate the slope of a landscape cell along a particular direction, sloping flow connectivity acts as follows:

$$\frac{\delta L_s(x, y, \varphi(L_0))}{\delta \vec{v}(x, y)} = \frac{D_v}{D_h} \quad (10)$$

where  $D_v$  and  $D_h$  are the vertical and horizontal distances between the center-point of the focal cell and the center-point of the adjacent cell in the specified direction.

Sloping flow connectivity takes a reasonably simple approach to estimate the % slope of a cell in a particular direction: it assumes that the elevation values for all cells are good estimates of the elevation at the center-points of the cells. If the direction is not a cardinal direction, then the slope is calculate from the focal cell center-point to an interpolated point between 2 adjacent cell center-points. It can also be calculated in degrees using the following alternative equation:

$$\frac{\delta L_s(x, y, \varphi(L_0))}{\delta \vec{v}(x, y)} = \arctan\left(\frac{D_v}{D_h}\right) * \frac{180}{\pi} \quad (11)$$

Which is the ecological meaning of the slope direction (also known as, slope aspect or slope orientation) calculated over the frictional landscape  $L_s$ ? Clearly, it represents the least friction direction (LFD) to species dispersal. To calculate the aspect from the frictional landscape  $L_s$ , I have used the equation from Evans (1972):

$$LFD = \arctan\left(-\frac{\frac{\delta L_s(x, y, \varphi(L_0))}{\delta y}}{\frac{\delta L_s(x, y, \varphi(L_0))}{\delta x}}\right) \quad (12)$$

which is the angle by the  $x$  and  $y$  derivative of  $L_s$  via  $arctan$ , measured clockwise in degrees from North. Once LFD is calculated, it can be then grouped into 9 categories (flat; N: 337.58–22.58, NE: 22.58–67.58, E: 67.58–112.58, SE: 112.58–157.58, S: 157.58–202.58, SW: 202.58–247.58, W: 247.58–292.58, NW: 292.58–337.58).

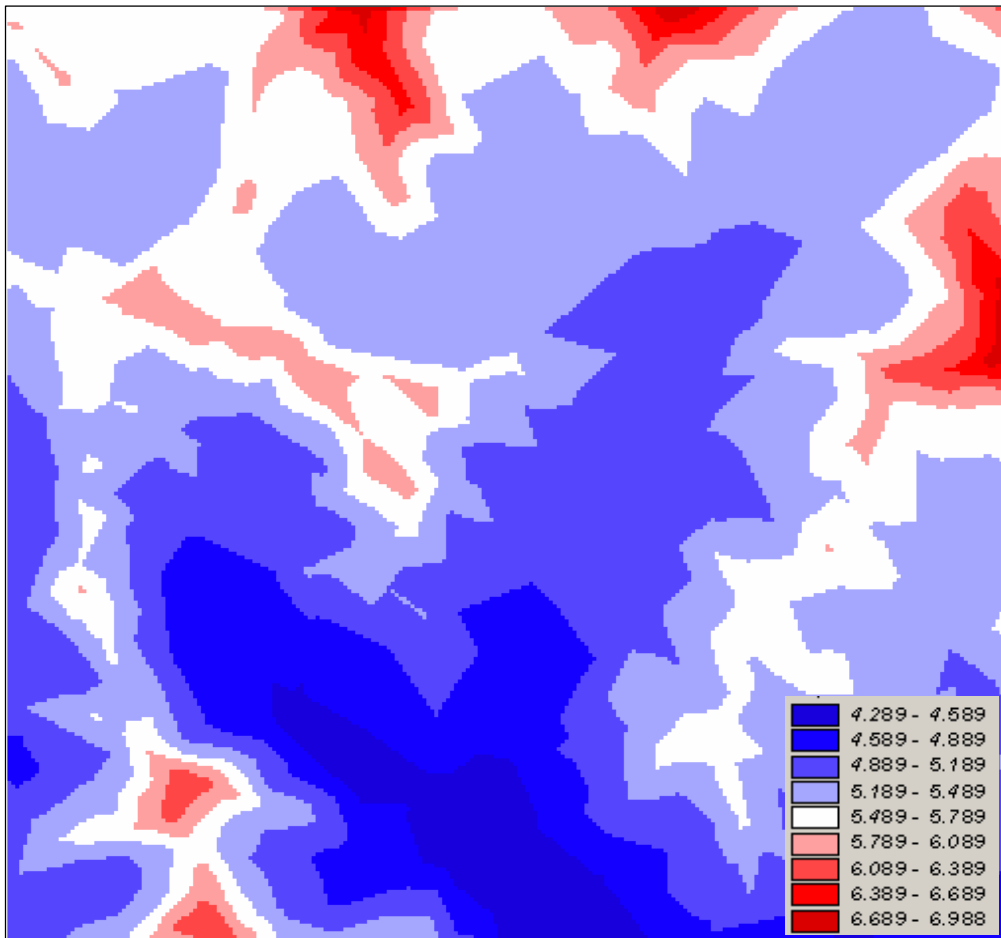
In order to apply sloping flow connectivity modelling to real landscapes, I wrote the *ad hoc* software Connectivity Lab (Ferrarini, 2013f).

### 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 widely analysed (Ferrarini and Tomaselli, 2010; Ferrarini, 2011b; Ferrarini, 2012c; Ferrarini, 2012d).

From an ecological viewpoint, the most interesting event registered in the last years is the shift of wolf populations from the montane belt to the lowland. Several populations have been recently observed *in situ* by life-watchers, environmental associations and local administrations.

As an example of sloping flow connectivity, I have applied my model 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 recently observed. The area is a square of about 20 km \* 20 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. A discussion of wolf's frictional coefficients is outside the goals of this paper, so I avoid presenting them.

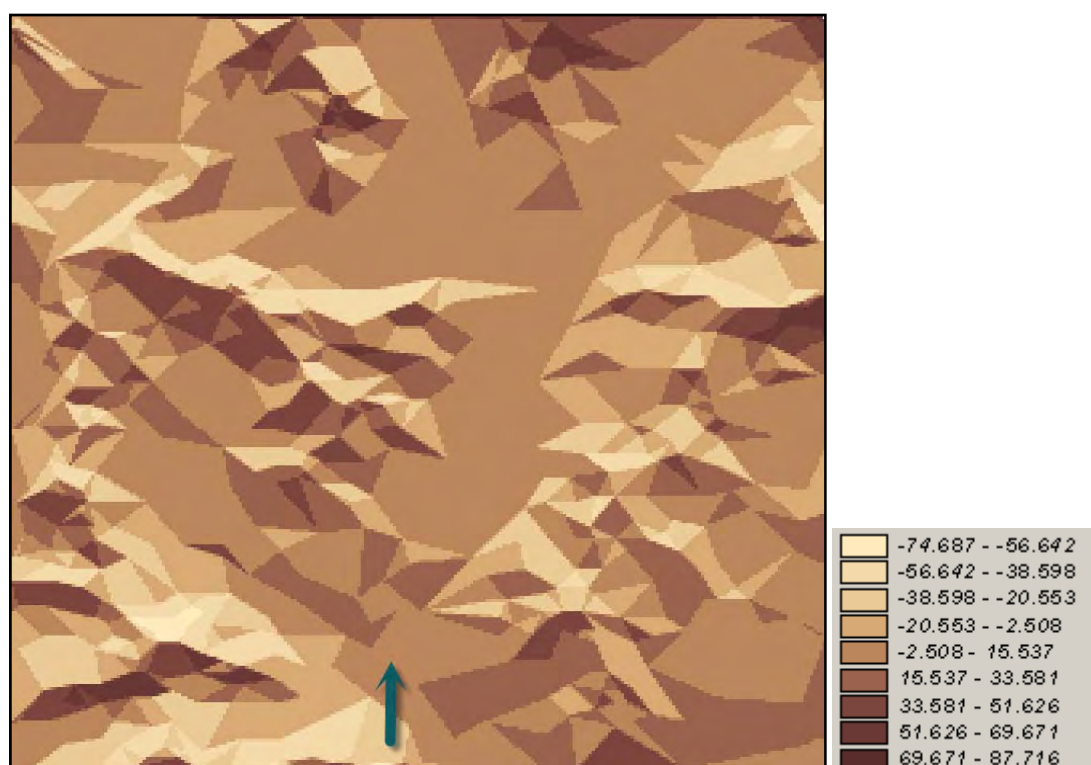


**Fig. 1** The frictional landscape  $L_s$  has been built for wolf upon a 20 km \* 20 km portion of the Ceno Valley (province of Parma, Italy) that represents here the real landscape  $L(x,y,z,t)$ . The higher frictional values are in red, the lower ones are in blue. The frictional landscape has been built using both structural and functional properties of the landscape (Ferrarini, 2012e).

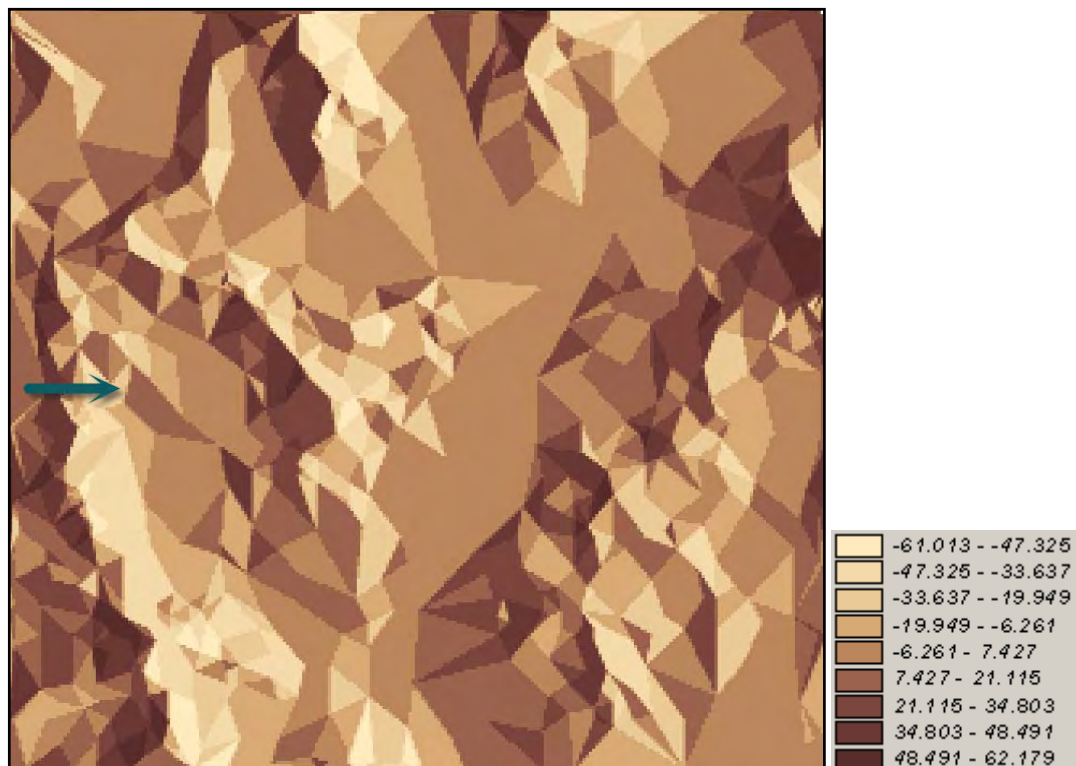
In order to simulate (directional) species movements along such landscape, I calculated sloping flow connectivity along the 4 cardinal directions (N, S, E, O) using equations from (8) to (12).

Simulated northward (i.e.,  $a=0$  and  $b=1$ ) connectivity is depicted in Fig. 2. Darker areas depict the individuated barriers, lighter ones are the detected facilities. Barriers to northward wolf's movements are present in particular in the Eastern and Western portions of the study area. Instead, the central part of the study area present less problems to northward wolf's movements.

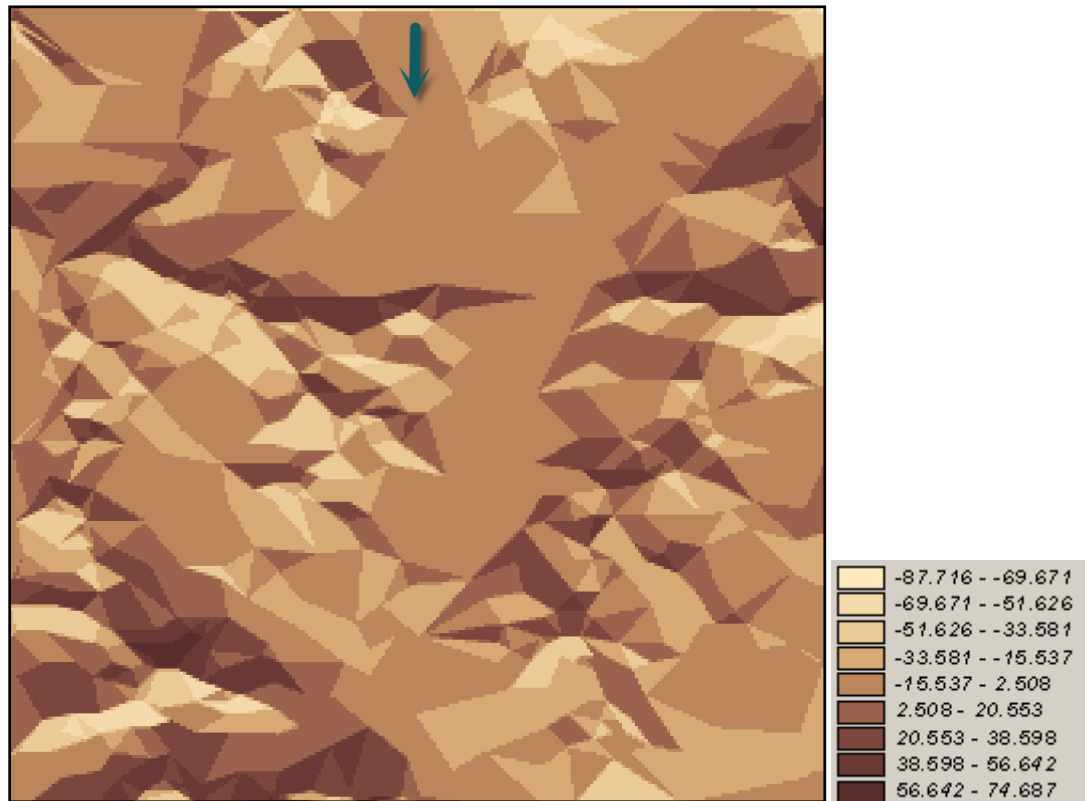
Simulated eastward (i.e.,  $a=1$  and  $b=0$ ) connectivity is depicted in Fig. 3. It is clear that the study area is particularly knotty with regard to eastward movements. Only the central portion allows for facilitated eastward shifts. Southward ( $a=0$ ,  $b=-1$ ) and westward ( $a=-1$ ,  $b=0$ ) movements are simulated in Fig. 4 and Fig. 5. Barriers and facilities are clearly detected.



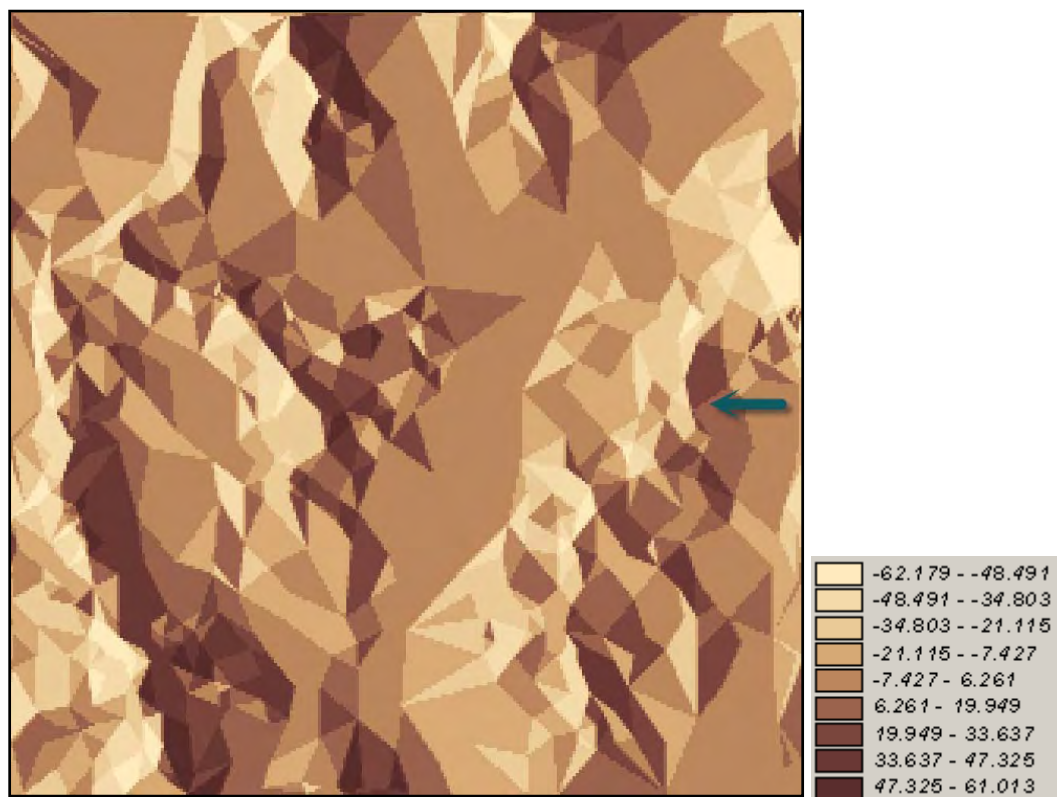
**Fig. 2** Simulated wolf's northward movements (as indicated by the arrow). Darker areas represent the individuated barriers, lighter ones are the detected facilities.



**Fig. 3** Simulated wolf's eastward movements (as indicated by the arrow). Darker areas represent the individuated barriers, lighter ones are the detected facilities.



**Fig. 4** Simulated wolf's southward movements (as indicated by the arrow). Darker areas represent the individuated barriers, lighter ones are the detected facilities.

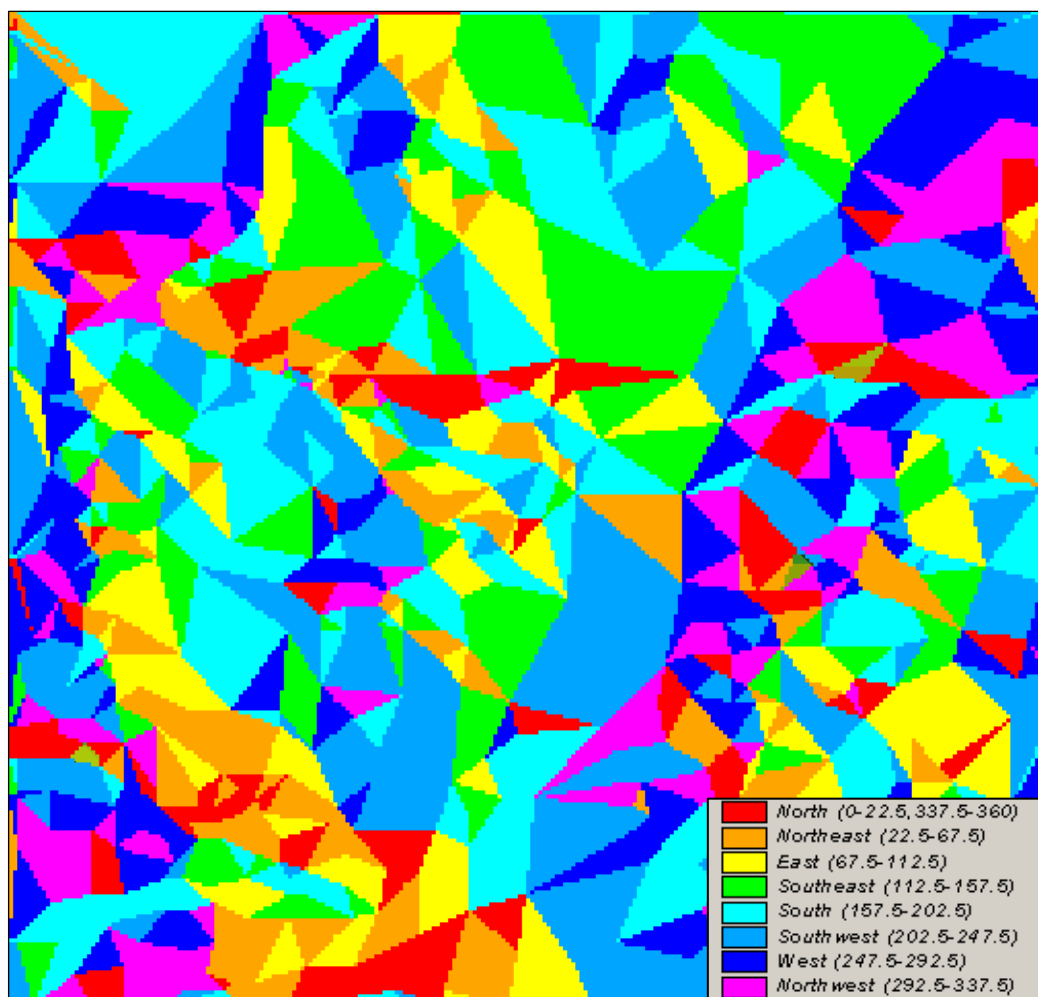


**Fig. 5** Simulated wolf's westward movements (as indicated by the arrow). Darker areas represent the individuated barriers, lighter ones are the detected facilities.



The computation of the *LFD* for the frictional landscape  $L_s$  using eq. (12) depicts for each portion of the study area the most facilitated direction for wolf (Fig. 6).

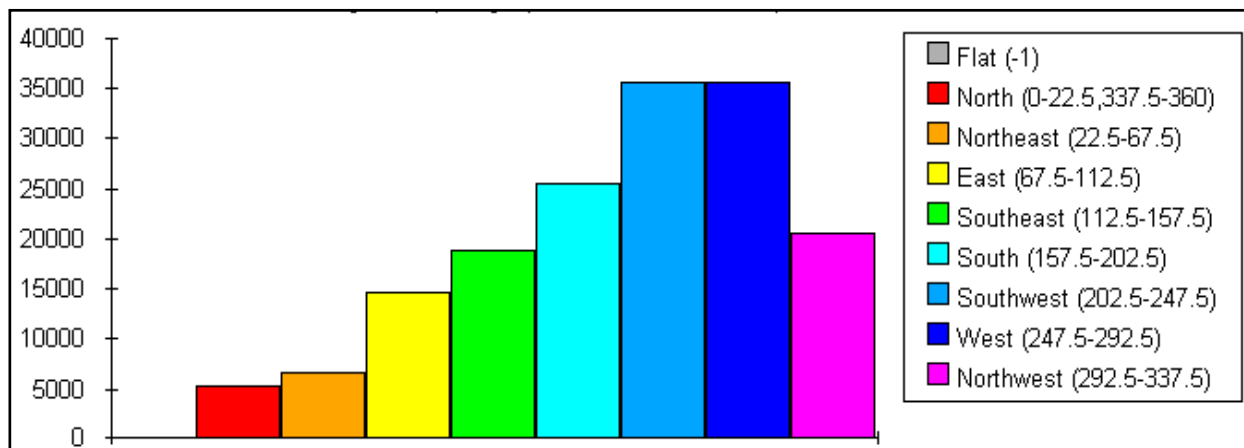
It results clear that wolf's movements towards South, South-West and West are the most probable (i.e. facilitated) events in the study area. Instead, wolf's movements towards North, North-East and East are highly improbable. It's also clear that there's a kind of spatial clustering of movements probabilities, with certain directions prevalent in particular portions of the study area (Fig. 6).



**Fig. 6** Map of the most facilitated wolf's movements in the study area. It has been achieved via sloping flow connectivity applied to the frictional landscape  $L_s$  of Fig. 1. For each pixel, the direction with the lowest friction to species dispersal is given.

The overall assessment of the least friction directions to wolf's dispersal in the study area is given in Fig. 7, which refers to Fig. 6.





**Fig. 7** Histogram of the most facilitated directions to wolf's dispersal in the study area. Columns count the number of pixels in the sloping landscape of Fig. 6 with a particular direction for the most facilitated wolf's dispersal.

#### 4 Conclusions

Planning greenways and ecological networks in an effective manner is not an easy task, since it requires to detect the real potential of each landscape elements to facilitate or obstruct both directional and overall species movements. Conservation practitioners use two main strategies to promote connectivity. The first focalizes on conserving areas that facilitate movement, the second focuses on restoring connectivity across areas that impede movement. Most connectivity works have focused on the former strategy.

In this paper, I have introduced sloping flow connectivity that is on top of this requirement, as it is able to produce simple and effective maps of barriers and facilities to directional and overall species dispersal. Sloping flow connectivity takes advantage of two previously-introduced theoretical and methodological frameworks for the prediction of species dispersal: flow connectivity and reverse flow connectivity.

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