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PATH NETWORK MODELLING AND NETWORK OF AGGREGATED SETTLEMENTS:
A CASE STUDY IN LANGUEDOC (SOUTHEASTERN FRANCE)

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1 INTRODUCTION

The possibilities and constraints on the movement of people and goods is a key factor that determines practices and structures space. The evolution of the communication network is therefore very important for understanding the evolution of a region. Our study aims to analyse the changes in the pattern of ancient aggregated settlements through communication network modelling. The reconstruction of the ancient communication network is a means of understanding the evolution of this pattern not as a succession of creations and abandonments of settlements – point maps – but as a changing network.

The study area is located in Languedoc (southeastern France) and extends from the Mediterranean coast to the hills of the hinterland (Fig. 1). In coastal regions, the communication network is traditionally associated with sea and river freight. However, this paper deals with the road network at the regional scale, not with trade at Mediterranean level. In addition, it should be noted that the extent of navigability on local rivers in the periods under study is open to question; for example, the most important river of the study area – the Vidourle river – was navigable only during high water before its embankment from the plain from the Middle Ages onwards. The road networks have therefore played a major role in trade at the regional level in this area.

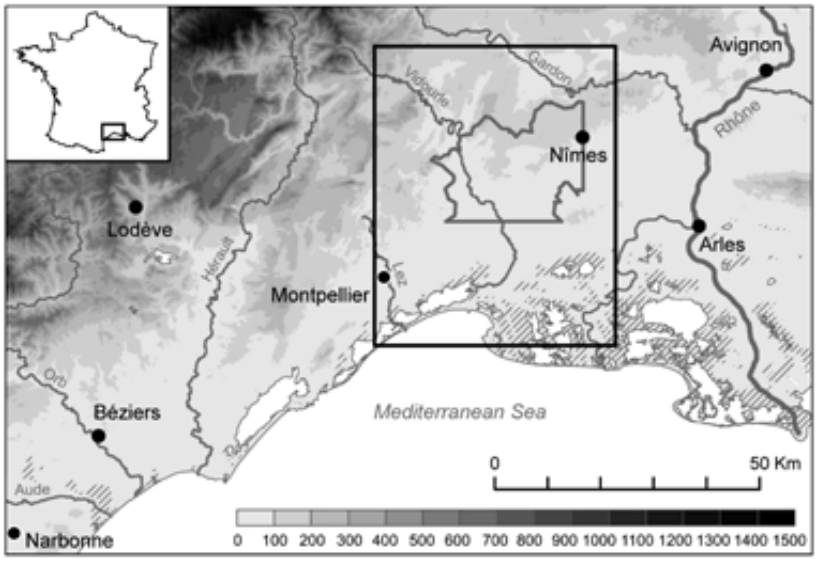

Fig. 1 | Study area and subset for settlement pattern analysis

Thanks to numerous previous studies, we have a good overview of the ancient settlement distribution and dynamic in most of the study area (Favory *et al.* 1985; Favory *et al.*1994a; Durand-Dastes *et al.* 1998; Nuninger 2002). However, knowledge of the ancient road network in this region is still deficient (Fig. 2). Research has long focused on the axis of long-distance communication connecting Italy to Spain through southern Gaul, known as the *Via Domitia* (from the Rhone to the Pyrenees), also called the "Heraclean road" in the context of the prehistoric periods. In the study area, its itinerary is reported by ancient sources (literary and epigraphic) and most of its course has been reconstructed from its milestones (Castellvi *et al.* 1997). However, inter-regional roads – the "medium" level of the communication network – are still poorly known. Following G. Charvet, it is generally considered that the major communication routes – linking Nîmes to other capital cities – follow approximately the course of present-day roads (Charvet 1873; Clément 2003; Monteil 1999; Provost *et al.* 1999; Fiches 2002, 21, fig. 4). It is also assumed that transhumance paths and medieval salt and pilgrimage roads were used from Roman or prehistoric times (Clément 2003; Favory *et al.* 1985; Favory *et al.* 1994b; Fiches 2002, 80–81). At the same time, in some areas, map and photointerpretation studies carried out at local scale propose numerous possible Roman paths (Parodi *et al.* 1987; Bonnaud / Raynaud 1994; Raynaud 2002), since the communication network seems to be well preserved in the landscape of this region: the archaeological sites are indeed often close to present paths. It is nevertheless very difficult to define the status of these hypothetical segments of ancient roads in the ancient communication network: were they part of the regional network or local paths between farms?

These reconstructions of ancient routes are based on regressive methodology[1], which starts from present-day elements of the landscape and selects tracks identified as being related to the periods under study. However, there is very little evidence to date the use of these old roads. Moreover, studies on roads have shown that the routes change, mainly because of attraction by later settlements, and may undergo minor or major course changes (Vion 1989). Roads have a history and their course results from a long and complex evolution that combines abandonments, changes in status and reactivations (Vion 1989, 89). That is the reason why the number of proposed routes for a given regional road increases in areas where precise studies have been carried out (see box in Fig. 2).

The knowledge yielded by a regressive approach is too scant to handle ancient road networks: the chronology and status of known roads are uncertain and many major connections remain to be located. Therefore, we adopted a constructive approach. Optimal path modelling, that is, simulating the connections between contemporary archaeological sites, helps to apprehend the whole communication network in its relative chronology and hierarchy.

[1] This kind of methodology uses the position of places of interest (river crossings, settlements), landscape analysis and toponymy. It results in the assembly of various segments of linear elements in the present landscape, interpreted as remnants of old routes.

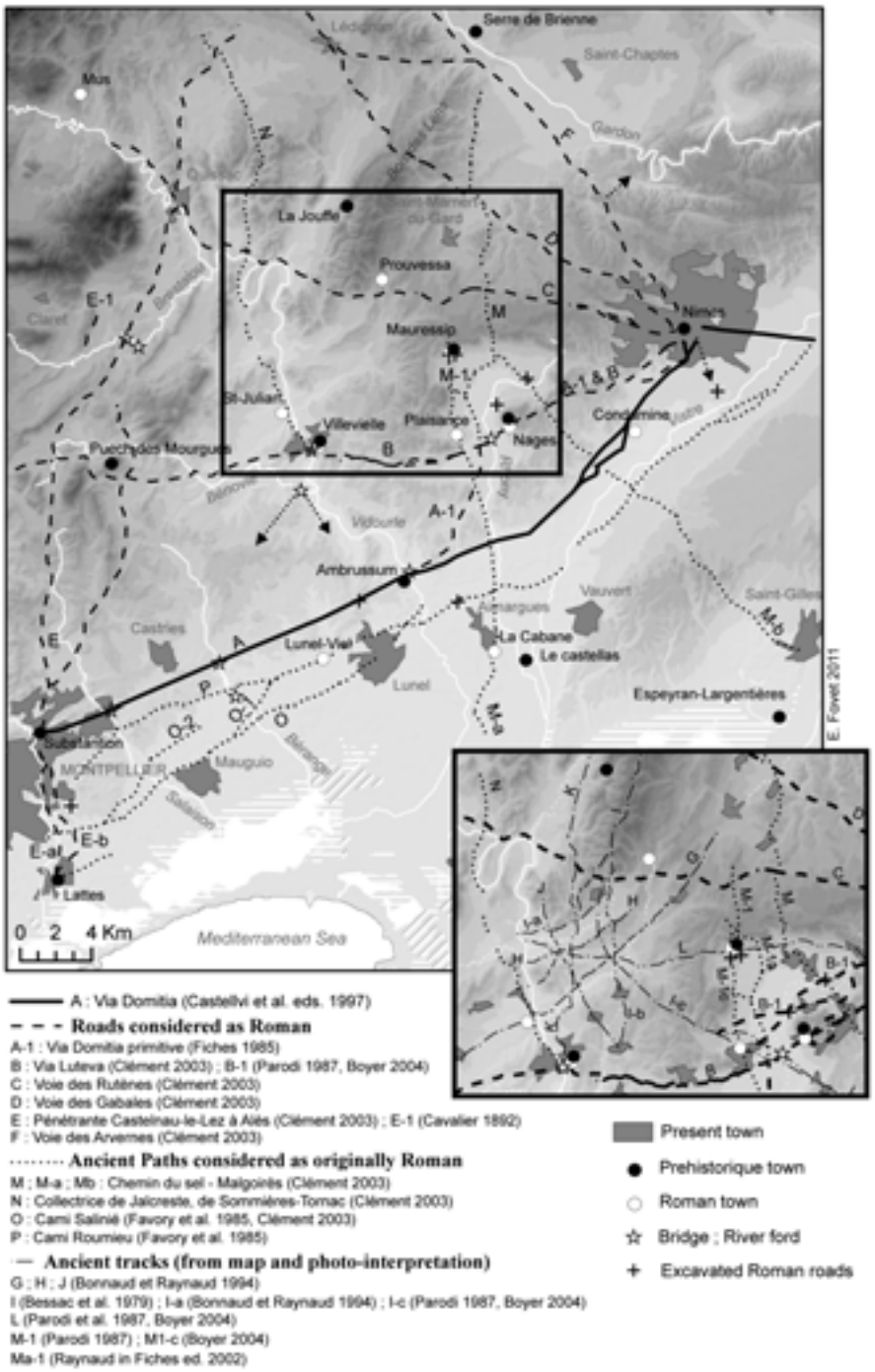

Fig. 2 | Roads traditionally considered as Roman.

In contrast to the methods that have previously been used to study the road network in Languedoc, the aim of modelling is not to find the ancient roads in a precise manner, but to locate the communication channels that potentially result from the distribution of settlements. Optimal path modelling helps determine the most plausible path between two places, taking into account factors affecting mobility. In a further step, the computation of optimal paths

between a set of places – optimal path network modelling – gives the structure of a network; the multiplication of modelled paths highlights the communication channels which, according to the factors considered, are the most likely: that is, development in the form of roads is most likely where the intensity of trade is potentially highest.

Our goal was not to study the numerous paths, built or not, that connect all settlements, but rather to trace the main communication channels that cross the region. This scale of analysis restricted the study to a specific level of the network and guided the choice of sites for path modelling. The regional level of the communication network has been modelled from the distribution of the agglomerations. Our selection of the major sites is based upon the collective research programme "L'habitat groupé gallo-romain et les agglomérations secondaires en Languedoc-Roussillon" (Fiches 2002). These sites can be very large or quite small (2 ha or less), nevertheless they all present evidence of specific status, such as the organizational structure of buildings, the presence of religious activity, epigraphy, etc. It is acknowledged that agglomerations played an important role in the spatial organization of the territory of Nîmes between the capital city and rural settlements (Fiches 2002, 15). So occasionally we will call these sites "centres," referring to centres of gravity of the economy or population

2 Optimal path implementation

The factors and parameters taken into account in this work are mainly chosen according to the environmental characteristics of the interior of Languedoc: they are based on topography. The routes sought correspond to the least constraint path; in addition, the impact of a perceptual factor was tested: the field of view. To do so, two least cost path modelling methods were used.

2.1 Optimal path factors

From the perspective of travel by land, several categories of factors can be considered. First, we assume that the paths must be cost effective: they should enable fast movement, while energy consumption when travelling should be low. In fact, we assume that the difficulty of a journey was more important than travel time for the periods considered – especially since in the region the distance between the agglomerations in Roman times is only 25 km on average.

The basic constraints on movement are considered usually as topography (slope), as well as the existence of barriers such as rivers, or surface conditions (vegetation, a built road, swamp, etc.). However, apart from the difficulties related to our poor knowledge of hydrography and surface conditions in ancient times,[2] we can consider these factors as secondary, to the extent that various construction techniques were used (bridges, land stabilization, forest clearance etc.). We do not aim to simulate the effect of movement of an individual in a given context, but to assess the strong constraints imposed by a space travelled frequently by communities. From this perspective, we can consider that the

[2] We know that in the study area river fords have moved significantly since the periods studied (Clément 2003, 26), especially as a result of the hydrological system of this north Mediterranean karstic region. In addition, our knowledge of the palaeoenvironment is limited and it is still not possible to map ancient vegetation and wetlands reliably.

topography is the primary element.

Energy consumption also depends on the means of transport considered. To simplify the implementation, only pedestrian locomotion has been taken into account to set the least cost path modelling. Of course, the use of a cost function for wheeled vehicles would change the structure of the communication networks produced by theoretical modelling, due to different critical slopes (Herzog 2013). Nevertheless, we assume that a model based on pedestrian movement can already give a good assessment of the potential for the organization of the communication network.

Second, energy consumption is not the only variable that influences human travel (Llobera 2000; Wheatley / Gillings 2002, 151, 155). For this study, we have considered that a path providing a good field of view will be preferred by travellers transporting goods – inert, or live, such as herds – for orientation and safety reasons. We assume that it is one of the factors in the establishment of roads in elevated places (as better perceptual conditions would counterbalance the topographical difficulties). When implemented, the "visual" factor is usually based on viewshed analysis (Lee / Stucky 1998; Lu et al. 2008). We however prefer to apprehend this factor through the field of view (FOV). Like energy consumption, this factor is conditioned by topography (see infra).

2.2 Slope-dependent least cost path calculation

Various solutions have been proposed to weight the distances depending on slope (for a comprehensive review of the various algorithms used in archaeology see: Van Leusen 1999; Van Leusen 2002, 6.5–6.7; Wheatley / Gillings 2002, 154–156). Like others previously (Llobera 2000; Podobnikar et al. 2004), we relied on biometric measurements: the energy consumption values relating to movement on slopes were based on the results of a physiological study made on mountaineers (Minetti et al. 2002). The range of slope gradients given in Minetti's paper is quite broad, so we modelled intermediate cost values using a polynomial function of 3rd degree.

The relative energy consumption calculated according to the slope value is an anisotropic parameter. Therefore, the slopes should not be considered as a set of fixed values, since the friction of movement is always dependent of the direction of movement: there are strong differences when walking up, down or along the slope. The problem of the difference between energy consumption walking up or down the slope is sometimes treated partially by introducing an offset on symmetric functions, so that the cost of walking down the slope is smaller than walking on flat terrain (Verhagen et al. 1999; Van Leusen 2002, 16.10–16.18). Some circumvent the issue by considering that a path is a round trip (De Silva / Pizziolo 2001). However, it can be argued that, for a round trip, one would choose the best option by considering separately the costs for each direction; these costs cannot be reduced to an average cost, as has been proposed in some studies (De Silva / Pizziolo 2001). Moreover, it is also possible to follow different paths depending on the direction of movement.

Taking into account the direction of motion in path modelling has long posed technical difficulties. It is not enough to offer different cost values for walking up and down slopes, it is still necessary to know the direction in which the slope will be traversed during each trip. Some commercial GIS software allows anisotropic calculations, such as the ESRI's Path Distance method, which can calculate the effective slope for each combination of two pixels from their respective elevation values ("vertical relative moving angle": ESRI 2009). This

effective slope is then transformed using a "vertical factor," which can be defined by a table correlating cost values with slope categories (in our case based from the energy expenditure values published by Minetti et al.). However, the integration of one or more additional factor(s) affecting movement can be problematic, because this tool provides only one way to combine the effects of the slope and any other cost component(s), namely multiplication. Theoretically, there is no dependency between the parameters we have chosen; the FOV (field of view) factor is not more important on a steep slope than on flat terrain. Therefore, addition is a more suitable method of combination than multiplication.

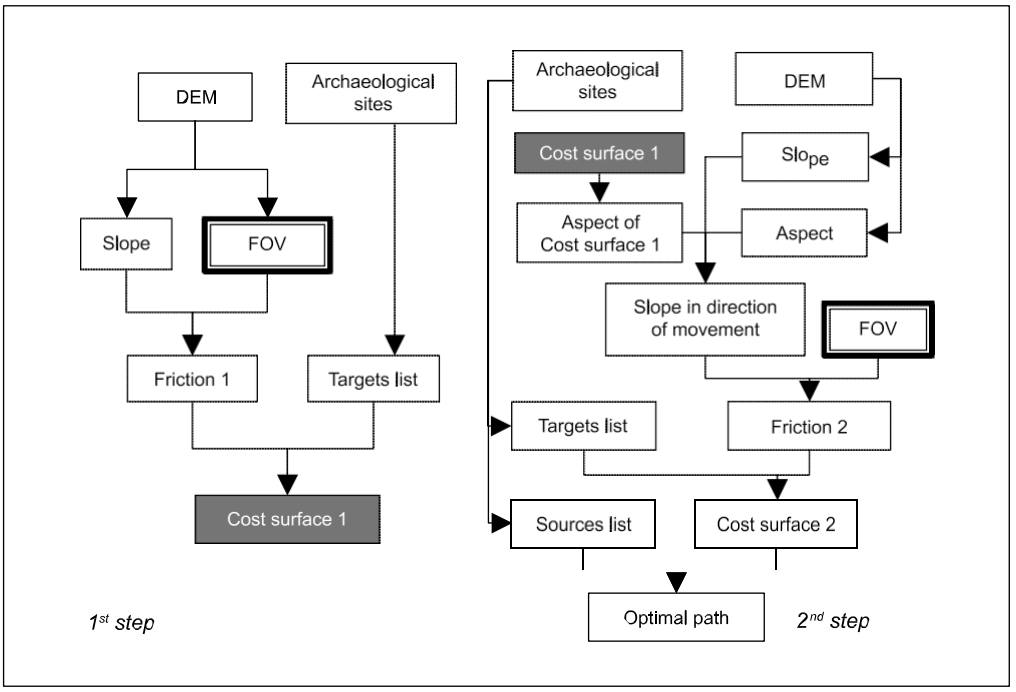

Fig. 3 | Proposed procedure for ancient path modelling

Our approach proposes a specific anisotropic procedure: it considers the (approximate) direction of movement during the calculation of the friction surface. This procedure consists of two main steps (Fig. 3), in order to predict the approximate direction of movement between two places which might differ significantly from a straight line. The first step consists in computing a temporary accumulated cost surface (*cost surface 1*). In the second step the approximate direction of movement is estimated by the calculation of the aspect of the temporary accumulated cost surface; this allows us to calculate the effective slope from which we performed a final accumulated cost surface using an isotropic algorithm (ESRI's *Cost Distance*), and then the least cost path.

The calculation of the effective slope is based on the cosine of the difference between the aspect of the relief and the direction of the movement (*aspect of cost surface 1*). When the difference between the aspect and the direction of movement is equal to 90° (i.e. when walking along the slope) the recalculated slope is null, when this difference is equal to 0° (i.e. when walking up the slope) the value remains unchanged, and when this difference is larger than 90° (i.e. when walking down the slope) the recalculated slope has a negative value.

$$slope_{recalc} = \cos(aspect_{relief} - direction) \cdot slope$$ (Zakšek *et al*. 2008)

The resulting paths are quite different from those obtained with the ESRI's Path Distance method (e.g. Fig. 4). They are "smoother," exhibiting fewer topographical variations than the ESRI's modules. In the region studied, consequently, the proposed procedure tends to generate elevated paths, following the ridges. In contrast, the Path Distance method generally produces quite straight paths, hardly influenced by the topography; this favours the transition into lowlands and narrow valleys. The analysis of all the modelled tracks (between a set of agglomerations) showed that the communication channels produced by these two procedures represent different types of paths that we also find in the actual landscape.

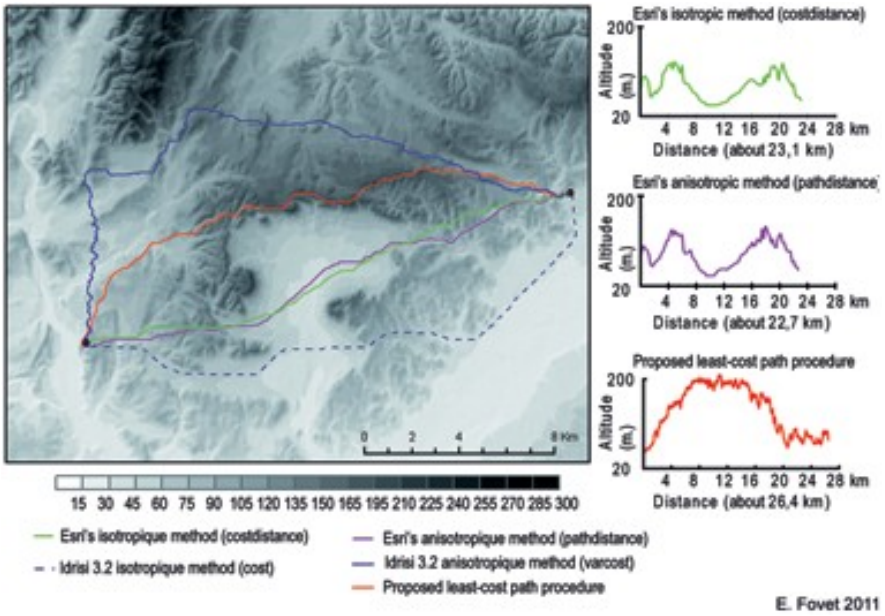

Fig. 4 | Comparison of the different least-cost path procedures

We consider that the differences with the ESRI's anisotropic method do not undermine our least cost paths procedure, although it is true that in very complex topographical conditions (with craggy relief) our procedure causes unnecessary detours. In these rare cases, however, the introduction of the field of view (FOV) factor improves the model significantly.

2.3 Introduction of the field of view factor

The field of view (FOV) has been defined as the average angle of horizon (Fig. 5). It was computed by searching the horizon at the maximum distance of 7 km in 32 directions on 360°, with a methodology similar to skyview factor computation (Yokohama et al. 2002; Zakšek et al. 2011; Kokalj et al. 2011). Areas with the average angle of horizon close to zero do not have many obstacles in their horizon (such as plains, ridges etc.), and areas with a high average angle of horizon provide a low field of view (as in narrow valleys or piedmonts).

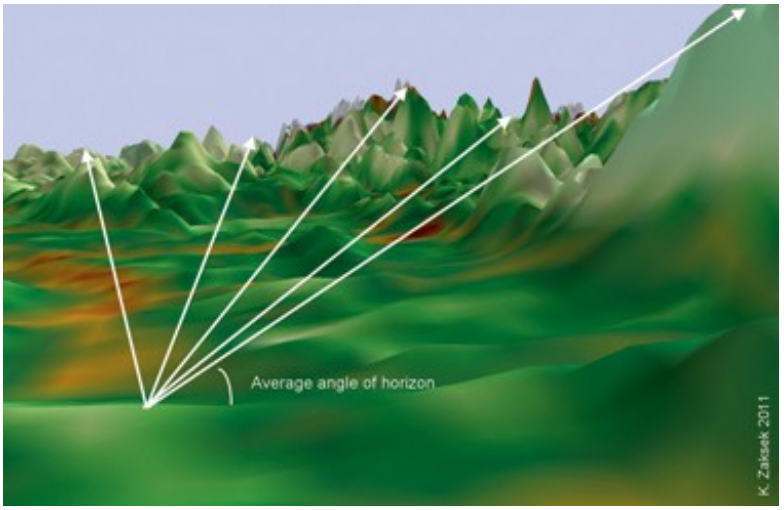

Fig. 5 | FOV as the average angle of horizon (drawing by K. Zakšek)

In order to obtain optimal paths that take into account both the effect of the slope and the impact of the field of view, the friction surface was calculated as a sum of the FOV and the relative energy consumption weights (see supra). However, the impact of the FOV on human decisions about movement is not measurable. It is hence essential to evaluate the combination of the FOV and energy consumption factors. We computed several models, changing the weight of the field of view:

In the first model, the FOV was set to 1; this model yields a very poor influence by the FOV, as its values are much lower than the energy consumption ones – FOV values range from 1 to 27.7, with a mean of 2.87, while those of energy consumption range from 24 to 356, with a mean of 33. A second model was produced using a FOV weight of 5; the values of this layer are still two times lower than the energy consumption ones. In the third model, FOV weight was set to 10, which yields a strong influence by the field of view since the values of the two factors are then similar. In the fourth model FOV weight was set to 20; the values of this layer are two times higher than the energy consumption ones.

The introduction of the FOV to the modelled tracks gathers the paths either on the ridges or in the centres of plains and basins.

3 Assessment of the models

3.1 Comparison with roads previously proposed as ancient

Path modelling validation is a difficult issue. The relationship between network models and roads considered as ancient (e.g., presumed Roman) is ambiguous: if a modelled channel does not fit the presumed path for a given route, one cannot really know if that is because the model is erroneous or because the route traditionally proposed corresponds to another period or another level in the road network (local roads and inter-regional roads vs. regional communication channels). The status of roads implies specific routes, because the main purposes are different (e.g., supra-local roads do not aim to connect all local places), the level of engineering and the organization are variable and the modalities of transport can also be different (pack animals vs. wheeled vehicles for bulky goods). Inevitably, several alternative

routes existed and our modelled networks are designed to locate only one of them. Thus, at the present state of studies on ancient roads in Languedoc, optimal path modelling cannot really be tested against the roads considered to be ancient; conversely, however, models can provide an analysis of the roads considered to be ancient.

The *Via Domitia* is an interesting example for the problem of the confrontation between the road network models and the known ancient roads. We know that this interprovincial road was constructed during the 2nd century BC (see *supra*); however, it is now generally considered that this was even then an adaptation of a pre-existing route (Py 1990, 623; Clément / Peyre 1991, 15–25; Castellvi *et al.* 1997, 16; Py/Vignaud 1998). In our region, its path can be divided into two parts (see Fig. 2): the section *Sextantio-Ambrussum* and the section *Ambrussum*-Nîmes. Close to Nîmes, its precise location is subject to discussion (Fiches 1985, 136–138; Fiches 1997, 63; Laforgue *et al.* 1997, 24).

Road	Section	Total length (km)	Pathdistance	Proposed procedure	Proposed procedure + FOV	Proposed procedure + (FOV x 5)	Proposed procedure + (FOV x 10)	Proposed procedure + (FOV x 20)
A	*Sextantio-Ambrussum*	21.9	20.2	21.4	17.5	16.4	11.9	7.3
A	*Ambrussum*-Nîmes	20. 9	3.7	1.7	1.5	15.2	15.5	15.6
A	*Ambrussum*-La Condamine-Nîmes	20.9	17.9	11.7	12.9	13.4	15.5	15.6
A-1	*Ambrussum*-Nage-Nîmes	17.6	11.1	11.8	11.1	6.7	6.8	6.9

>75% of the total length
>50% of the total length

Fig. 6 | Length of the longest optimal path segments of the network that follow the *Via Domitia* (with a tolerance of 500 m)

The *Sextantio-Ambrussum* section of the *Via Domitia* is followed, by and large, by the various optimal paths between these two towns (Fig. 6), with the exception of those from the model strongly influenced by our visual factor (FOV set at 20). In contrast, to model the path of the *Ambrussum*-Nîmes section, it seems necessary to integrate the FOV with a significant weight – directing the optimal paths in the open plain. For the other models the only way to reconstruct the *Via Domitia* correctly is to take into account the small town of La Condamine as a stopping point. Archaeologists usually consider that the section connecting *Ambrussum* to Nîmes has changed over time. According to J.-L. Fiches (Fiches 1985, 136–138; Fiches 1997, 63) its passage in the plain could not have been put in place before the layout of the cadastre "Nîmes A" to which the road fits securely, that is to say from the 1st century BC on. It was proposed as early as 1930 (J. Igolen) that the pre-Roman path passed via the oppidum of Nages, 5 km to the north of the *Via Domitia* (see Fig. 2, road A-1). This proposed pre-Roman route is more readily reproduced by the paths from our least cost procedure (without the

integration of the FOV): optimal path segments are a bit longer, but mostly much denser.

Road	Section	Total length (km)	Pathdistance	Proposed procedure	Proposed procedure + FOV	Proposed procedure + (FOV x 5)	Proposed procedure + (FOV x 10)	Proposed procedure + (FOV x 20)
B		48.8	15.5	12.6	12.0	8.9	7.7	7.8
C	Mus-Prouvessa	16.5	14.9	3.3	7.3	10.7	8.5	6.1
C	Prouvessa-Nimes	20.3	14.4	8.7	11.7	14.7	9.3	10.5
D		31.0	20.1	3.7	4.1	15.2	15.4	11.2
F		19.3	9.4	4.9	4.2	10.9	4.5	4.5
E		52.2	17.8	9.8	9.7	9.2	9.4	8.3
E-2		18.3	5.5	7.1	6.8	7.1	7.8	6.9
B-1		15.8	9.3	4.7	3.3	4.0	3.4	3.4
G		17.9	8.5	5.3	4.0	13.4	9.2	8.4
H		7.9	3.6	7.9	7.0	6.7	6.9	6.7
I		17.2	2.6	10.2	11.4	6.5	3.4	3.0
I-a		7.2	2.6	6.0	6.0	5.2	0.0	0.0
I-b		8.1	0.0	3.2	6.7	4.3	6.5	6.2
I-c		22.1	7.8	4.7	9.3	2.1	2.1	2.1
J		8.0	6.3	4.3	4.3	5.9	5.8	7.4
K		16.8	11.9	6.6	8.3	5.1	0.0	0.0
L		16.2	11.5	5.5	5.7	4.9	4.4	4.3
M		15.8	15.7	4.2	2.4	5.7	3.0	3.0
M-a		26.4	13.6	11.6	13.7	16.2	13.8	14.0
M-b		25.1	10.4	8.2	12.5	7.3	4.8	7.4
N		24.8	8.1	4.0	4.5	5.4	4.5	6.3
O		54.5	10.8	8.2	8.2	8.0	8.1	11.0
P		21.6	10.5	6.3	8.7	11.3	6.4	6.4

>75% of the total length
>50% of the total length

Fig. 7 | Length of the longest optimal path segments of the network which follow the roads previously proposed as ancient (with a tolerance of 500 m)

Concerning the rest of the road network, we observe that, in general, optimal paths follow approximately the tracks of the roads considered to be ancient[3] (Fig. 7), although they do not always correspond to dense channels. The communication channels produced by the Path Distance method correspond better to the presumed inter-regional Roman roads (roads C, D and F). Regarding the other types of road, some are better represented by this model (B-1, K, L and particularly the ancient salt roads M), while others are better represented in the networks modelled using our least cost path procedure (G and particularly H and the transhumance paths I). Considering the specificities of the paths modelled by our procedure, it is not surprising that they are the only ones that fit to the ridge paths (H, I and I-a).

These comparisons let us see that no model alone can approach the complex ancient road network; the use of several models completing each other is needed. In some cases historical reconstitution of a single road requires that different parameters be modelled. For example, the section Nîmes-Nages of the inter-regional road B is best fitted by our procedure when the visual factor is given no, or a very small, weight (FOV set at 0 or 1). Its Nages-Villevieille section is followed only by the "*Path Distance* model". For the section Villevieille-Puech des Mourgues, models using our procedure are the best (especially with FOV set at 1 or 5).

As a further step, the analysis of optimal path network modelling at regional scale shows that some inter-regional roads are likely formed by connecting up separate regional routes. Let us take the example of the road D, which connects Nîmes to *Anderitum* (nowadays Javols in Lozère): its section between Nîmes and the massif of Bois des Lens (in the north of La Jouffe) is represented in the majority of the models (*Path Distance*, models with FOV set at 5, 10 or 20) as a portion of the route between Nîmes and Mus. We can therefore propose that this section of the inter-regional road D corresponds primarily to the regional roads from Mus to Nîmes, to which the route from *Anderitum* would connect.

The road C also seems to be composed of the regional routes from Nîmes to Prouvessa and La Jouffe on one hand, and from Mus to Mauressip, Nage and Espeyran on the other hand. The connection between these two sections is poorly represented by modelling pathways between the regional centres. It is therefore interesting to note that in the area where these regional networks connect (south of Prouvessa) this road makes a detour (Fig. 8). This area is also marked by a Late Roman funerary area and the proximity of a Roman and Late Roman settlement. This detour is obviously not caused by the topography and could well be an artefact of the evolution of the road network. In fact, the segment oriented southeast to northwest of this anomaly corresponds to the channels connecting the *oppida* La Jouffe and Mauressip, which serve a set of iron ore processing sites and high quality stone quarries in the massif of Bois des Lens (Fig. 8).

[3] Only roads E, N, O and B are not well represented

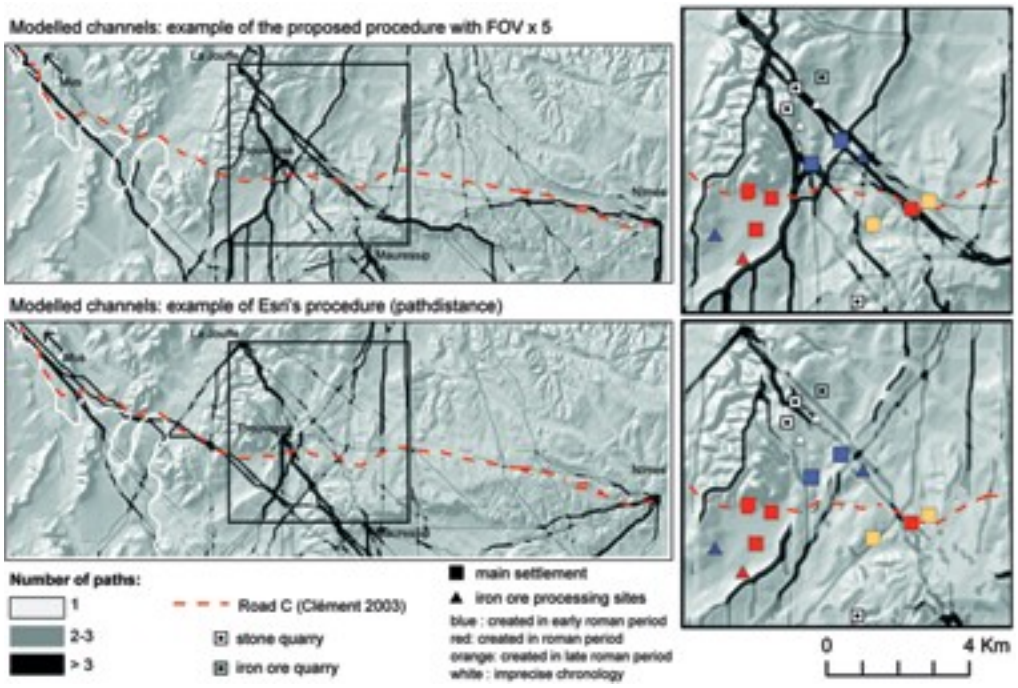

Fig. 8 | Enlarged view of road C and the modelled channels

We can therefore assume that the linkage of the two old roads has been influenced by the existence of other routes passing nearby. At present, there is no element that would allow us to fully understand this phenomenon of interaction between the different levels of roads (local, regional…): only more data for the southwest to northeast communications would be able to support this hypothesis. In any case, the comparison between this road and the network models suggests that the axes of passages in this sector are complex; the tracks could have swung between the attraction of long-distance networks and the logic of regional or local communications, and could well have had a story much more dynamic than is indicated by the regression analysis of the road network.

The confrontation between the road network models and the roads considered as ancient raises interesting questions but, as we said above, it does not help to validate or invalidate the different models.

3.2 Comparison with the settlement pattern

Another way to evaluate the different regional road network models is to observe their consistency with the entire settlement pattern at different periods. Indeed, it can be assumed that the road network was a significant factor for the choice of location of many sites. For a farm, the vicinity of a major road made it possible to market its produce more easily and probably lowered the financial cost of transport. Latin agronomists paid special attention to the "commodity" of transport in the rural economy:

> A handy road contributes much to the worth of land: first and most important, the actual presence of the owner, who will come and go more cheerfully if he does not have to dread discomfort on the journey; and secondly its convenience for bringing in and carrying out the necessaries – a factor which increases the value of stored crops and lessens the expense of bringing things in, as they are transported at lower cost to a place which may be reached without great effort; and it means a great deal, too, to get transportation at low cost if you make the trip with hired draught-animals, which is more expedient than looking after your own; furthermore, that the slaves who are to accompany the master will not be reluctant to begin the journey on foot. (Columella, *RR I*, transl. H.B. Ash 1941).

In order to evaluate the models we calculated the frequency of archaeological sites[4] in a range of distance bands from the main communication channels, for four different periods which represent the major phases of evolution of the settlement pattern in this region: the 5th century BC, the 2nd BC, the 1st AD and the 5th AD. To do this, we abstracted the main channels from the path networks obtained, using the density[5] of paths. We started by mapping the densest channels (which represent 5 or 6 paths, or 4 paths for certain periods), then we proceeded by completing gaps in these main pathways by following the most dense channels in between (usually 3 or 4 paths, or sometimes 2 paths). In certain cases, where two agglomerations were not connected with this procedure, we lowered the first threshold (3 or 4 paths). We restricted this analysis to the core of the study area (Fig. 1); this subset of 452 km2 is free of border effects and corresponds to the hilly zone of the interior of Languedoc (the type of environment for which the model was developed) where the archaeological data are most reliable.

Except for the 5th century BC, a proportionally large quantity of sites is situated at less than 800 m from the main modelled channels, while in zones at more than 1200 m the number of archaeological sites declines (Fig. 9). About 40 % of the sites are situated in one of the first two ranges of distance in most periods. We note that this percentage is quite stable despite the strong variation in the numbers of sites between the different periods. Indeed, there are ten times more sites occupied in the 1st century AD than during the 2nd century BC, but the proportions of sites inside the corridors are similar.

For the 5th century BC, the model which seems the most appropriate is the one built with our least cost path procedures without taking into account the visual factor (FOV weight set at 0). For all other periods, the "*Path Distance* model" is the one that has most sites in the corridor of 400 m, while our least cost path procedures obtain better correlation

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[4] Excluding those used as nodes to model the optimal path network

[5] Defined by kernel density of optimal paths within a radius of 125 m

between 400 m and 800 m when the visual factor is given no, or a very small, weight (FOV set at 0 or 1). Models that take into account the FOV significantly (weight of 5 or 10) are suitable for the 2nd century BC and 1st century AD, but less so for the 5th century AD.

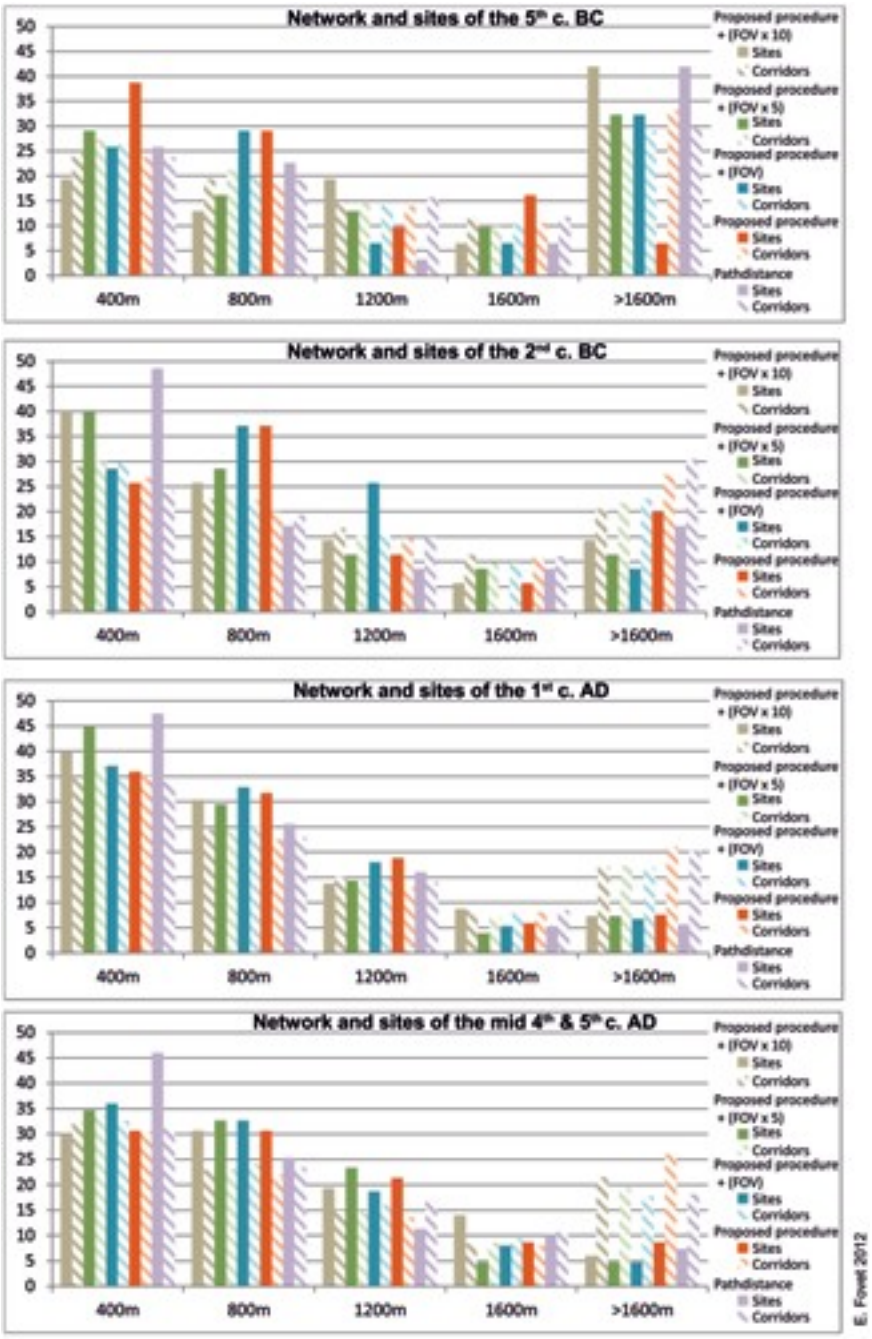

Fig. 9 | Road network models and settlement pattern: proportions of sites located in distance bands from the main communication channels (plain colours) and proportions of landscape taken up by these zones (hatched colours)

A relationship appears between the types of sites[6] and the network models (Fig. 10). For the prehistoric periods, it is difficult to determine whether the various models concern specific types of sites, because the number of sites is low. One can nevertheless note that in the 2nd century BC ephemeral sites (class A) predominate in the models in which the visual factor is given no, or a very small, weight (FOV set at 0 or 1), while class B is slightly overrepresented in the vicinity of the "*Path Distance* model".

In the 1st century AD, distributions of classes for each model are quite similar to the analysed corpus. One can nevertheless note that modest settlements (class A and B) tend to be over-represented in the models from our procedure, whereas this tendency is reversed for the "*Path Distance* corridors," where class E (higher status settlements) and C (medium size settlements occupied for a long time) are better represented. For the end of the 4th and during the 5th century AD, distributions of classes for each model show stronger differences. Higher-status settlements (class D and E) are better correlated with models without a visual factor, while smaller and short-lived sites (class A or B) are under-represented. Conversely, in the vicinity of models that integrate the visual factor significantly (FOV multiplied by 5 or 10), ephemeral sites (class A) are clearly over-represented while long-lived and large settlements (class C and D) are scarcer.

Overall, these two sets of charts show that from the 2nd century BC on, we observed far more small and ephemeral sites in the vicinity of the network models that integrate the visual factor and therefore favour elevated places or mid-plain, especially the model where the FOV is multiplied by 5. In contrast, the network of pathways that is relatively uninfluenced by the topography and which favours the transition into lowlands (produced with the *Path Distance* method) is more strongly related to large and sustainable settlements. This suggests that we modelled two types of network that seem to have had separate functions, since they not only reflect different ways of moving, but also appear to serve specific categories of archaeological sites. This phenomenon may be related to rural activities, such as pastoralism, but the characteristics of settlements attached to these models should be studied in greater detail before proposing a firm link to this type of path network.

These results let us consider the coexistence of two different kinds of network, each governed by a specific logic of movement (and probably with different aims and means of transport). Therefore, we decided to use the two most typical models to study the evolution of these regional path networks: a "model A" built with Path Distance and a "model B," which corresponds to the model that integrates the visual factor and which proved to be the most attractive, or specifically related, to ephemeral sites, i.e., the model that gives a moderate but significant weight to this factor (FOV weight set at 5).

[6] This analysis uses the results of a classification of the settlements (from the 7th century BC to the 7th century AD) made on a supra-regional scale (using a corpus localized in different micro-regions in southeast and central France) during the ArchaeDyn 2 programme (Bertoncello et al. 2012). This classification is mainly built on the highly discriminating variables "surface" and "duration of the occupation" of the settlements

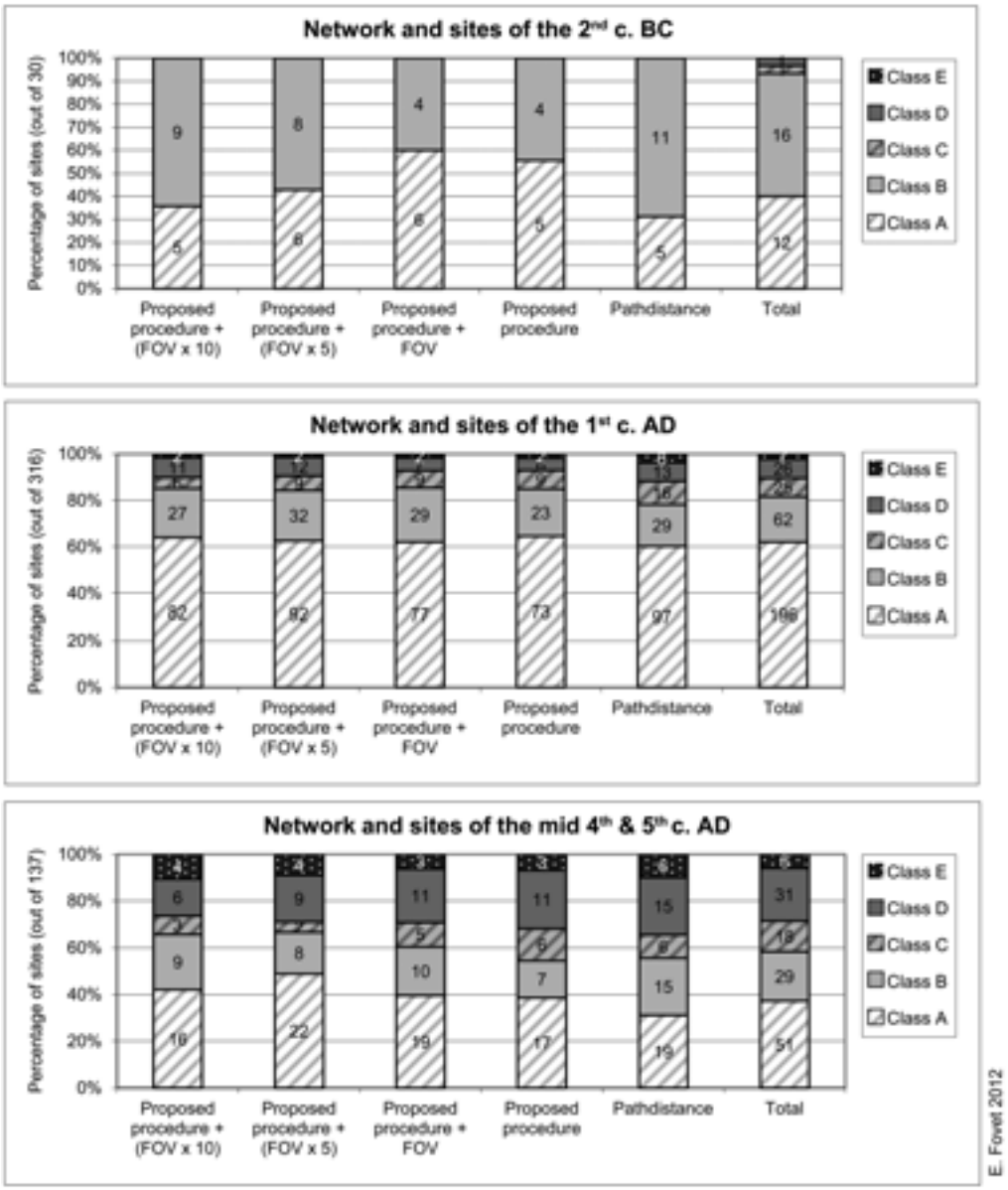

Fig. 10 | Road network models and settlement pattern: types of sites located in a corridor of 400 m from the main communication channels (hierarchical classification from *ArchaeDyn2* programme)

4 EVOLUTION OF THE OPTIMAL PATH NETWORKS

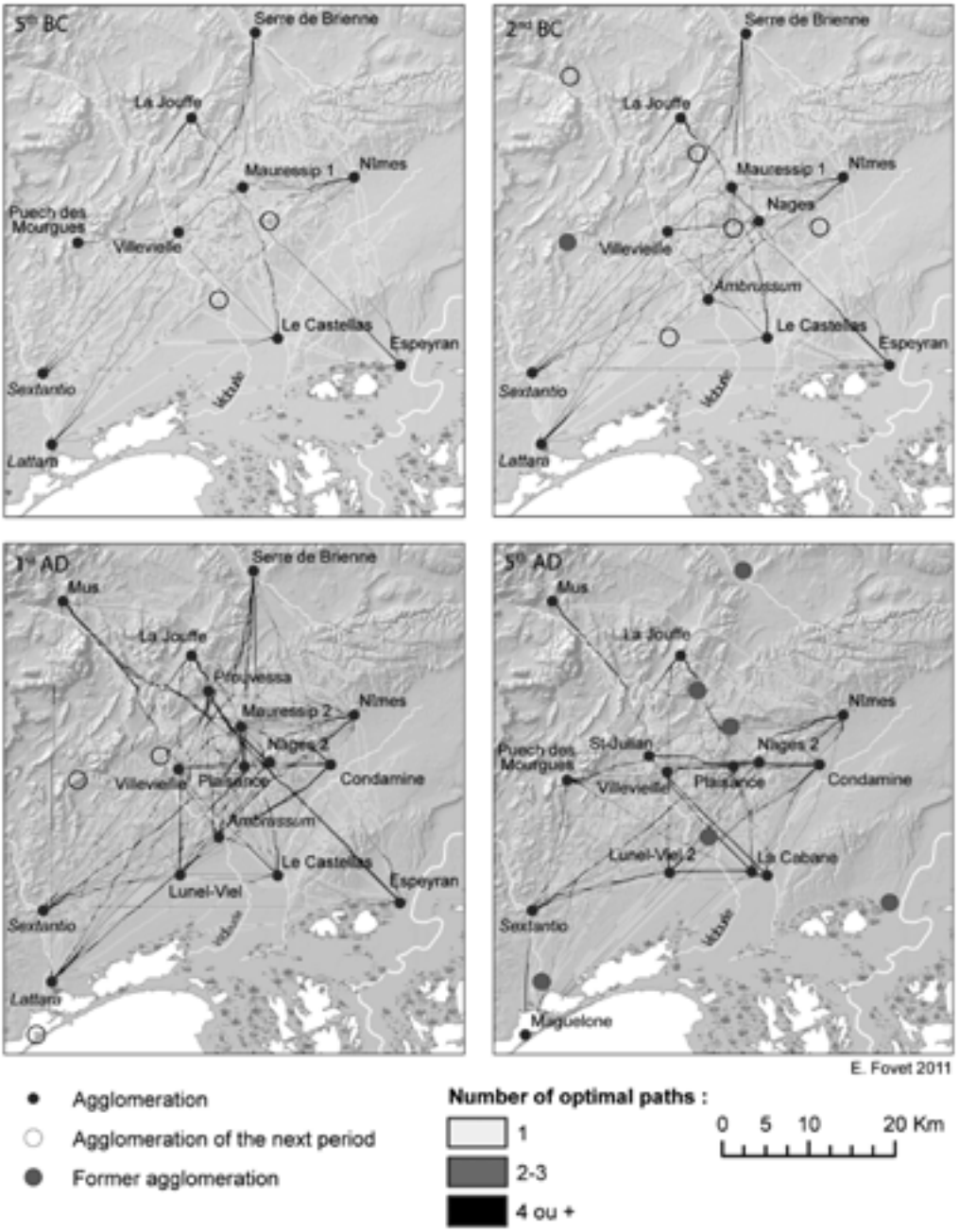

Fig. 11 | Road network models from the 5th century BC to the 5th century AD: model A

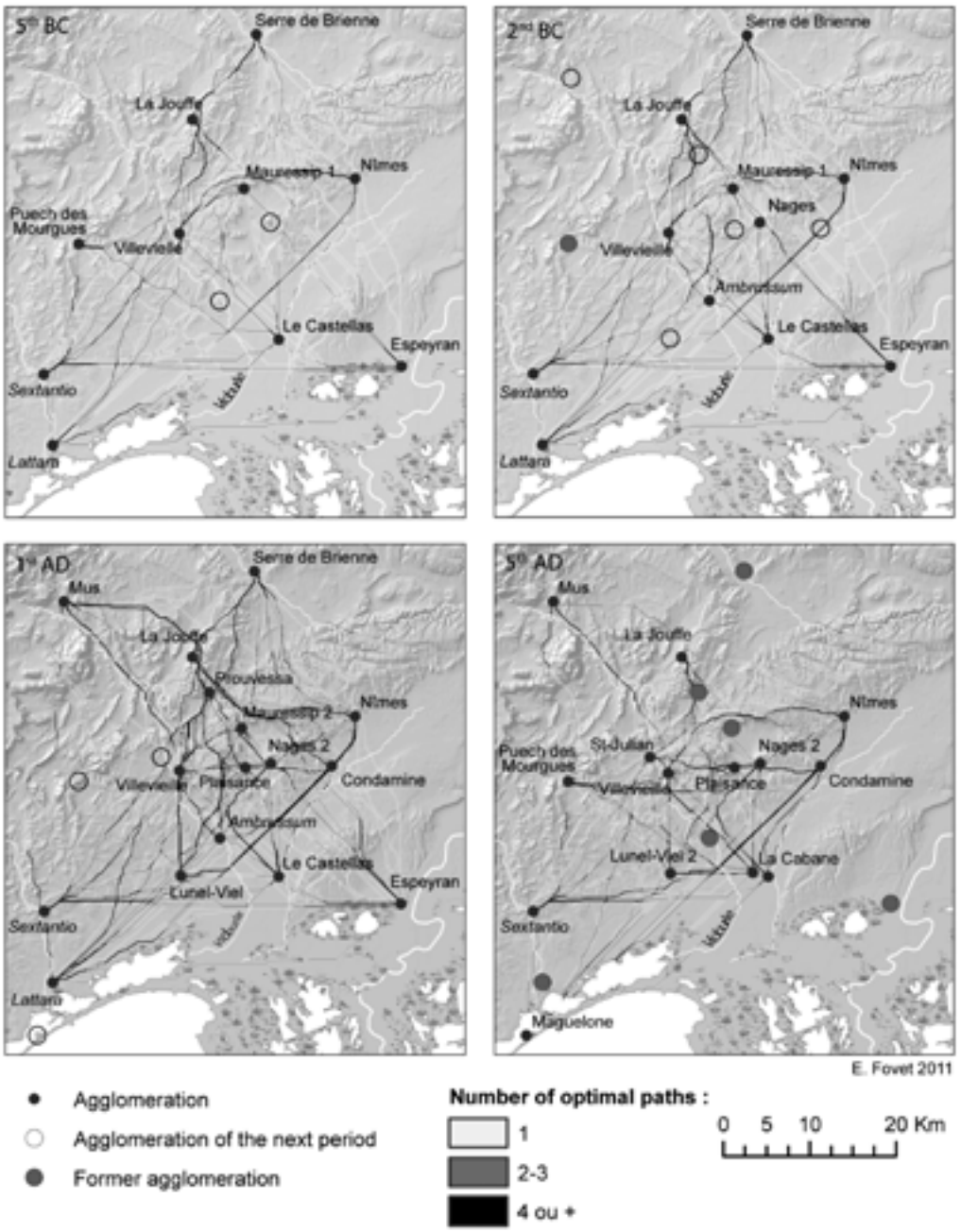

Fig. 12 | Road network models from the 5th century BC to the 5th century AD: model B

The evolution from the 5th century BC to the 1st century AD of the distribution of the agglomerations produces only very slight changes in the configuration of the regional optimal path network in both models (Fig. 11 and Fig. 12). This apparent stability shown by the optimal path models over these periods suggests that new agglomerations did not really change the structure of the road network but more likely completed it. The oppida of the second Iron Age (settled between the late 4th and early 3rd centuries BC) as well as the small

towns created during early Roman times (from the end of the 1st century BC and especially during the early 1st century AD) were established along the previous communication channels (especially in model A). This suggests that the major settlements created during these periods were established in the vicinity of ancient roads. Thus these centres seem to have benefited from pre-established communication structures, and did not necessitate the construction of additional roads to trade and exchange with other important places.

However, the establishment of these early Roman towns also seems to have influenced the appearance of (or at least reinforced the existing trend of) alternative routes to the previous agglomerations. This tendency is more pronounced in model B. This phenomenon is particularly noticeable in the case of the oppidum of *Ambrussum*, around which the network model B forms four points of intersection within a radius of 3 km (Fig. 12). The existence of alternative pathways is indeed likely in this case, as it may be that travellers wanted to avoid the legal constraints (passage fee) probably associated with crossing the river by the bridge[7] at the foot of the oppidum. Therefore we can assume that alternative channels (type B) coexisted with tracks connecting the oppidum to the other regional centres (notably the *Via Domitia* linking Nîmes to *Sextantio* and Lattes).

Beyond the overall stability of the network suggested by the optimal path models, the question that emerges concerns the role of new centres in the agglomeration network: were the new towns complementary to or competitors of the ancient ones?

The cases of *Ambrussum* and Lunel-Viel are interesting in this respect. Lunel-Viel was established to the southwest of *Ambrussum*, in the middle of the 1st century AD, at the intersection of pre-existing communication channels of the model A (Fig. 11), and where the alternative channels in the model B meet (Fig. 12). This let us consider that the establishment of Lunel-Viel resulted in channelling this second type of flow (B), probably on the track of road P (see Fig. 2 and Fig. 7). Therefore, Lunel-Viel would have had the effect of helping to better control the traffic circumventing *Ambrussum*. This hypothesis seems to be confirmed by the topography of this very small Roman town (Fig. 13): the road Cami roumieu (road P) penetrated from the east to the heart of the town and led to a large dead end furnished with monumental architecture, which suggests strong flow control on this road.

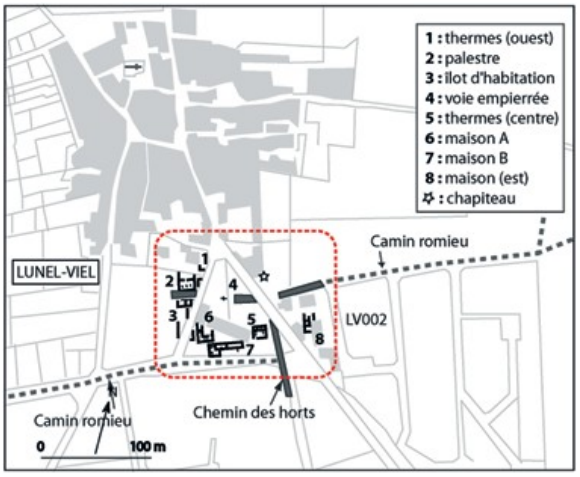

Fig. 13 | Lunel-Viel: spatial extent of the Roman town and roads serving the site (extract from Ouriachi 2009, vol. 2, from Raynaud 1990 and Raynaud 2007).

[7] On this Roman bridge see Vial 2003, 390–391, n° 1-I

From this point of view the new agglomeration seems to complete the role of the older centre. However, one may also wonder if, on the contrary, Lunel-Viel would not have rather had the effect of weakening the position of *Ambrussum* by reinforcing the alternative channels, especially since Villevielle, which is located further upstream, developed strongly from the 1st century AD.

On any scenario, there are parallels between the histories of *Ambrussum* and Lunel-Viel. *Ambrussum* witnesses great vitality in the 1st century BC, but the upper city was abandoned around the beginning of 2nd century AD, and only the road station located at the foot of the hill, where the *Via Domitia* passed by, lasted longer. In contrast, Lunel-Viel was created in the middle of the 1st century AD and witnesses a phase of intensification in the middle of the 2nd century AD (followed by stability until the middle of the 3rd century AD). Therefore, the decline of *Ambrussum* could be related to the potential competition exerted by Lunel-Viel (and other places?) at regional scale; or, at the least, the regional role of *Ambrussum* in the road network could have been transferred to Lunel-Viel. The existence of a long-distance communication axis (the *Via Domitia*) does not seem to have been sufficient to maintain the economic vitality of the *oppidum*: the place turned into a stopping point only. Path modelling cannot explain the decline of *Ambrussum*, but shows the likely role of the road network in the relationship between this site and Lunel-Viel. This aspect was not fully taken into account before, because the question of the roads was only addressed by the analysis of the roads traditionally regarded as ancient, which recognizes no direct connection between these two sites (see Fig. 2).

This example shows that optimal path network modelling can give new perspectives on the changing pattern of agglomerations: it leads us to rethink the relationship between these major settlements, and to reassess their relative position in the trade networks.

For the Late Roman period, the changes in the pattern of agglomerations do not seem to have a strong impact on the structure of the communication network either (Fig. 11 and Fig. 12). The abandonment or decline of several originally indigenous aggregated settlements between the end of the 1st century AD and the middle of the 2nd century AD produce only a decrease in the density of certain modelled channels, while the settling of St-Julian during the 3rd century AD and the reoccupation of Puech des Mourgues in the middle of the 4th century AD has only the effect of increasing the density of the east-west channels in the hinterland. This relative stability is partly due to the phenomena of slight displacements of population centres that do not affect the path network models – such as from Lunel-Viel to Lunel-Viel2, Lattes to Maguelonne, Le Castellas to La Cabanne and probably from Espeyran to another nearby site not included in the models because of uncertainties (St-Gilles). In addition, if the site of Puech des Mourgues did not appear very well integrated in the previous regional communication networks, St. Julian is located near a very old communication channel, which is found in the various prior network models. This stability suggests that abandonments or declines cannot be explained primarily by a restructuring of the regional road network.

However, we must be cautious regarding the Late Roman period, which should be studied using a wider range of settlements to fully perceive the evolution of the network of exchange. Indeed, the end of monumental architecture and euergetism makes the major places of this period much less easy to apprehend from archaeological data than for the previous periods, which are far better served by epigraphy and evidence of religious activity. The Late Antique central places are hence probably poorly represented in our modelling.

Therefore, at this stage of the study, we will make only preliminary observations:

We observe that the modelled channels for this period tend to pass via the location of former aggregated settlements that were not used in the calculation. The configuration of the general pattern of agglomeration would induce movement through (or close by) these sites anyway. The case of *Ambrussum* has already been discussed above: the road station is the only remaining settlement in the period studied, despite the fact that the place seems still to be well located in the regional path network; nevertheless its regional role may have been transferred to Lunel-Viel. The case of Mauressip is very interesting insofar as it seems to illustrate a process of the survival of some roads near abandoned sites: when new settlements are established along a pre-existing network (Nages and Plaisance in this case), they continue to maintain the structure of the road network, even if the original places are no longer active. Note that in the model A the perpetuation of the east-west road near the former *oppidum* (road L) seems due only to the existence of the Late Roman settlements (Puech des Mourgues and St-Julian); this raises the question of whether there was a process of reactivation of this track during the late Roman Empire.

5 Conclusion

The simulation of communication channels in this study was performed using several models. In addition to the use of common commercial GIS software, a procedure for calculating least cost paths has been proposed. In addition, the impact of a perceptual factor has been tested (the field of view).

The analysis of these models – from comparison with the presumed Roman roads, and consistency with the entire settlement pattern at different times – led us to consider the coexistence of two types of networks: a network of pathways relatively uninfluenced by the topography and rather straight, which favours the transition into the lowlands, and a network which integrates the visual factor, which favours elevated places. This second type of modelled network seems to have a separate function from the first: it does not just reproduce different way of moving but also tends to serve a specific category of sites, namely those of very short duration.

The two types of road network model can give new perspectives on the changing pattern of agglomerations. They show a slow construction of the road network from the Iron Age up to the early Roman period (1st century AD). *Oppida* of the second Iron Age and small towns created at the beginning of the Roman period fit into the networks modelled for previous periods: settled in the vicinity of previous communication channels, these agglomerations seem to benefit from pre-established communication structures. In this sense, the new major settlements did not really change the structure but completed it. Nevertheless, the models suggest that each introduction of new major settlements created or reinforced certain roads, or sections of roads, which offered alternatives to the old towns. Also, it is open to question whether these new agglomerations had the effect of channelling some of the alternative paths or weakening the position of the older towns in the communication network. This approach puts a different perspective on old questions about the evolution of the network of regional centres, driven by opposing logics of integration and competition.

For the late Roman Empire, however, the possible impact of the changes in the settlement pattern – characterized by the decline of several originally indigenous towns –

on the organization of the communication network are poorly identified by the modelling of recognized towns.

The confrontation between the road network models and the roads considered to be Roman has provided more questions than answers. At this stage of research on communication networks, the modelled results give a glimpse into a phenomenon of integration between different status of roads. The regional road network modelling shows that some inter-regional roads are likely formed by connecting up regional routes. In addition, some anomalies suggest that tracks could have swung between the attraction of long-distance networks and the logic of local communications, and could well have had a story much more dynamic than is indicated by the historical regression analysis of the road network. The intermediate level of the communication network (supra-local) – incorporating the role of large rural settlements – should be taken into account in order to test this hypothesis.

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References

Bertoncello, F. / Fovet, E. / Gandini, C. / Trément, F. / Nuninger, L. (2012)
"Spatio-temporal Dynamics of Settlement Patterns from 800 BC to 800 AD in Central and Southern Gaul: Models for an Interregional Comparison over the Long Term", in: C. Gandini / F. Favory / L. Nuninger (eds.), *ArchaeDyn: 7 Millennia of Territorial Dynamics. Settlement Pattern, Production and Trades from Neolithic to Middle Ages*. Proceedings of the Final Conference of the ArchaeDyn Project, Dijon, 23–25 June 2008, Oxford, 51-64.

Bonnaud, R. / Raynaud, C. (1994)
Rapport de prospection systématique n° 2. Moyenne vallée du Vidourle, communes de Combas, Fontanès et Souvignargues (Gard). Rapport de prospection pédestre, programme de prospection-inventaire "Vaunage Vidourlenque et Vistrenque" (1994–1998), Contribution à la carte archéologique du Languedoc oriental, SRA Languedoc-Roussillon, inédit.

Castellvi, G. / Comps, J.-P. / Kotarba, J. / Pezin, A. (eds.) (1997)
Voies romaines du Rhône à l'Èbre: Via Domitia *et Via Augusta,* Paris.

Charvet, G. (1873)
"Les voies vicinales gallo-romaines chez les Volques Arécomiques", in: *Bulletin de la société scientifique et littéraire d'Alès* V, 81–115 and 158–248.

Clément, P.-A. (2003)
Les chemins à travers les âges en Cévennes et bas Languedoc, Montpellier. First published 1983.

Clément, P.-A. / Peyre, A. (1991)
La Voie Domitienne. De la via Domitia *aux routes de l'an 2000*, Montpellier.

Columella
De re rustica. Trans. H. B. Ash (1941), London.

De Silva, M. / Pizziolo, G. (2001)
"Setting up a 'Human Calibrated' Anisotropic Cost Surface for Archaeological Landscape Investigation", in: Z. Stančič / T. Veljanovski (eds.), *Computing Archaeology for Understanding the Past*. Proceedings of the 28th Computer Applications and Quantitative Methods in Archaeology Conference, Ljubljana (Slovenia), 18–21 April 2000, Oxford, 279–286.

Durand-Dastes, F. / Favory, F. / Fiches, J.-L. / Mathian, H. / Pumain, D. / Raynaud, C. / Sanders, L. / Van der Leeuw, S. (eds.) (1998)
Des oppida aux métropoles. Archéologues et géographes en vallée du Rhône, Paris.

ESRI (2009)
Esri – ArcGIS Desktop 9.3 Help: Spatial Analyst. http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?topicname=how%20pathdistance%20works& (seen 17. 9. 2010).

Favory, F. / Fiches, J. L. / Raynaud, C. (1985)
"Occupation du sol entre Lez et Vidourle: approche des structures agraires dans la plaine littorale à l'époque romaine", in: *Etudes languedociennes*. Actes du 110e congrès national des sociétés savantes, Montpellier, 1985, Paris, 161–179.

Favory, F. / Girardot, J.-J. / Raynaud, C. / Roger, K. (1994a)
"L'habitat gallo-romain autour de l'étang de l'Or (Hérault). Hiérarchie, dynamique et réseaux du IIe s. av. au Ve ap. J.-C.", in: *Mélanges Pierre Lévêque* 8, 123–215.

Favory, F. / Parodi, A. / Poupet, P. / Raynaud, C. (1994b)
"Lunel-Viel et son territoire", in: F. Favory / J.-L. Fiches (eds.), *Les campagnes de la France méditerranéenne dans l'Antiquité et le haut Moyen Age*, Paris, 163–245.

Fiches, J.-L. (1985)
"Remarques sur le réseau antique dans la région de Nîmes", in: *Les routes du Sud de la France, de l'Antiquité à l'époque contemporaine*. Colloque du Comité des Travaux Historiques et Scientifiques 1, 135–143.

Fiches, J.-L. (1997)
"Le relais d'*Ambrussum*, de l'oppidum au Puech des Mourgues", in: G. Castellvi, / J.-P. Comps / J. Kotarba / A. Pezin (eds.), *Voies romaines du Rhône à l'Èbre: Via Domitia et Via Augusta*, Paris, 60–68.

Fiches, J.-L. (ed.) (2002)
Les agglomérations gallo-romaines en Languedoc-Roussillon. Publication du Projet Collectif de Recherche (1993–1999), Lattes.

Herzog, I. (2013)
"Theory and Practice of Cost Functions", in: F. Contreras / M. Farjas / F. J. Meleros (eds.), *Fusion of Cultures*. Proceedings of the 38th CAA Conference, Granada (Spain), April 2010, Oxford, 431-434.

Kokalj, Ž / Zakšek, K. / Oštir, K. (2011)
"Application of Sky-view Factor for the Visualization of Historic Landscape Features in Lidar-derived Relief Models", in: *Antiquity* 85, 263–273.

Laforgue, J. / G. Castellvi / J.-P. Comps (1997)
"Le tracé général", in: G. Castellvi, / J.-P. Comps / J. Kotarba / A. Pezin (eds.), *Voies romaines du Rhône à l'Èbre: Via Domitia et Via Augusta*, Paris, 23–36.

Lee, J. / Stucky, D. (1998)
"On Applying Viewshed Analysis for Determining Least-cost Paths on Digital Elevation Models", in: *International Journal of Geographical Information Science* 12(8), 891–905.

Llobera, M. (2000)
"Understanding Movement: A Pilot Model towards the Sociology of Movement", in: G. Lock (ed.), *Beyond the Map. Archaeology and Spatial Technologies*, Amsterdam, 65–84.

Lu, M. / Zhang, J. F. / Lv, P. / Fan, Z. H. (2008)
"Least Visible Path Analysis in Raster Terrain", in: *International Journal of Geographical Information Science* 6(22), 645–656.

Minetti, A. / Moia, C. / Roi, G. / Susta, D. / Ferretti, G. (2002)
"Energy Cost of Walking and Running at Extreme Uphill and Downhill Slopes", in: *Journal of Applied Physiology* 93(3), 1039–1046.

Monteil, M. (1999)
Nîmes antique et sa proche campagne, Lattes.

Nuninger, L. (2002)
Peuplement et Territoires protohistoriques du VIIIe au Ier siècle avant J.-C. en Languedoc oriental (Gard-Hérault), doctoral thesis in Archéologie, 2 vol., Université de Franche-Comté, Besançon. http://tel.archives-ouvertes.fr/docs/00/04/54/06/PDF/tel00002981.1these.pdf.

Ouriachi, M.-J. (2009)
Habitat, terroirs et territoire en Languedoc oriental durant l'antiquité. Approche spatio-temporelle d'un système de peuplement, doctoral thesis in Histoire, 2 vol., Université de Franche-Comté, Besançon.

Parodi, A. / Raynaud, C. / Roger, J.-M. (1987)
"La Vaunage du IIIe siècle au milieu du XIIe siècle. Habitat et occupation des sols", in: *Archéologie du Midi Médiéval* 5, 3–59.

Podobnikar, T. / Hvala, S. / Dular, J. (2004)
"Iterative Approach to Ancient Paths Modelling in the Iron Age Study of the Dolenjska Region (Slovenia)", in: K. Ausserer / W. Börner / M. Goriany / L. Karlhuber-Vöckl (eds.), *Enter the Past: The E-way into the Four Dimensions of Cultural Heritage*. Proceedings of the 30th Computer Applications and Quantitative Methods in Archaeology Conference, Vienna (Austria), April 2003. Oxford.

Provost, M. / Dedet, B. / Fabre, G. / Pène, J.-M. / Petitot, H. / Raynaud, C. / Roger, K. / Vidal, L. (eds.) (1999)
Le Gard. Carte archéologique de la Gaule, 30/2–3, Paris.

Py, M. (1990)
Culture, économie et société protohistoriques dans la région nîmoise, 2 vol., Rome.

Py, M. / Vignaud, A. (1998)
"Voie et habitat protohistoriques de Peyrouse à Marguerittes (Gard) (Ve siècle avant notre ère)", in: *Document d'archéologie méridionale* 21, 181–196.

Raynaud, C. (1990)
Le village gallo-romain et médiéval de Lunel-Viel, la fouille du quartier ouest (Annales littéraires de l'Université de Besançon), Paris.

Raynaud, C. (2002)
chapters "Mauressip, Saint-Côme-et-Maruéjols", "Nages, Nages-et-Solorgues", "Plaisance, Calvisson" and "*Varatunnum* (Saint-Julien), Salinelles", in: Fiches, J.-L. (ed.) (2002), *Les agglomérations gallo-romaines en Languedoc-Roussillon*. Publication du Projet Collectif de Recherche (1993–1999), Lattes, 595–361 and 651–655.

Raynaud, C. (2007)
Archéologie d'un village languedocien, Lunel-Viel (Hérault), du Ier au XVIIIe siècle, Lattes.

Van Leusen, M. (1999)
"Viewshed and Cost Surface Analysis using GIS", in: J. Barceló / I. Briz / A. Vila (eds.), *New Techniques for Old Times*. Proceedings of the 26th Computer Applications and Quantitative Methods in Archaeology Conference, Barcelona, March 1998. Oxford.

Van Leusen, M. (2002)
Pattern to Process: Methodological Investigations into the Formation and Interpretation of Spatial Patterns in Archaeological Landscapes, doctoral thesis, 2 vol., Rijksuniversiteit Groningen, Groningen. http://dissertations.ub.rug.nl/faculties/arts/2002/p.m.van.leusen/.

Verhagen, P. / Gili, S. / Micó, R. / Risch, R. (1999)
"Modelling Prehistoric Land Use Distribution in the Rio Aguas Valley (SE Spain)", in: L. Dingwall / S. Exon / V. Gaffney / S. Laflin / M. Van Leusen (eds.), *Archaeology in the Age of the Internet*. Proceedings of the 25th Computer Applications and Quantitative Methods in Archaeology Conference, Birmingham, April 1997. Oxford.

Vial, J. (ed.) (2003)
Le Montpelliérais. Carte Archéologique de la Gaule 34/3, Paris.

Vion, E. (1989)
"L'analyse archéologique des réseaux routiers: une rupture méthodologique, des réponses nouvelles", in: *Paysages découverts* 1, 67–99.

Wheatley, D. / Gillings, M. (2002)
Spatial Technology and Archaeology, the Archaeological Applications of GIS, New York.

Yokoyama, R. / Shirasawa, M. / Pike, R.J. (2002)
"Visualizing Topography by Openness: A New Application of Image Processing to Digital Elevation Models", *Photogrammetric Engineering & Remote Sensing* 68, 251–266.

Zakšek, K. / Oštir K. / Kokalj, Ž. (2011)
"Sky-View Factor as a Relief Visualization Technique", *Remote Sensing* 3(2), 398–415.