FONDATION POUR LES ÉTUDES ET RECHERCHES SUR LE DÉVELOPPEMENT INTERNATIONAL

Working Paper 358 October 2025 Development Policies

The Line and the Territory: modelling fragile border zones in the Sahel for a more inclusive border security management

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Abstract

This article discusses the representation of border areas in fragile and conflict-affected situations, particularly in the Sahel where borders have become spaces of competition between states and armed jihadist groups for the governance of border populations and cross-border movements. The spatial models available to represent border areas have many shortcomings, either because they are "administrative" and do not take into account the logics of movement that shape border spaces, particularly the movements of armed groups, or because they are too "naturalistic", inspired by environmental sciences, and take little account of human geography and conflicts. The article proposes a spatial model based on the representation of movement and transport networks that are at the heart of the border economy and describes the policy and operational advantages of its application to border security.

Keywords: borderlands, security, spatial networks, graph, spatial risk analysis.

LA FERDI EST UNE FONDATION RECONNUE D'UTILITÉ PUBLIQUE.
CETTE PUBLICATION A BÉNÉFICIÉ D'UNE AIDE DE L'ÉTAT FRANÇAIS AU TITRE
DU PLAN D'INVESTISSEMENT FRANCE 2030 PORTANT LA RÉFÉRENCE ANR-16-IDEX-0001.

How far does the border extend? How should the space around borders be controlled? The visualization of border zones is one of the prerequisites for shared border management (Payan and Cruz, 2017). Although the matter receives little attention in security crisis situations, the link between violence and the border is recognized in the literature on security (Starr and Most, 1983; Buhaug and Rod, 2006; Buhaug and Gleditsch, 2008) and on the economics of conflict (Stephenne et al., 2009; Raleigh, 2010; Schutte et al., 2014; Witmer et al., 2017; Linke et al., 2017; Moscona et al., 2018; Bruck et al., 2019).

What needs to be taken into account when managing border zones during a security crisis? The border is a symbolic and economic resource in the Sahel (Scheele, 2009), and continues to fulfil this role in a time of crisis (Cantens and Raballand, 2016). Trade flows rose by 25% in volumes between 2018 and 2020[1] at the border in Niger with Burkina Faso, while incidents with jihadists increased by a factor of five, rising from 48 to 250 within a 50 km strip either side of the shared border[2]. The figures for the same period were similar in Diffa (Niger), one of Boko Haram's operational areas, with an increase in cross-border trade of 45% and a fivefold increase in the number of incidents (from 23 in 2018 to 113 in 2020). Traders and border communities are adapting their practices, both formal and informal: trading activities in risk areas are carried out from the capital, emergency rules are circumvented by smugglers (but also by civil servants and corrupt military personnel[3,4]), internal refugees use small-scale cross-border trade as a subsistence source[5], and new trade routes are opened up in areas not under state control[6].

Owing to their existence outside state control and their persistent nature in economic and social terms, borders are therefore categorized as "fragile" and as spaces where competition takes place between states and armed groups for control over movements and the taxation of cross-border trade (both formal and informal) (Cantens, 2019 and 2021; Revkin, 2020).

Understanding and managing the border presupposes adequate visualization of the territory. At present, two types of spatial modelling are used (Schutte and Kelling, 2022); in our opinion, both are ill-adapted not only for operational purposes, but also for analytical and investigative work on fragile borders.

The first type is the administrative spatial model that divides up the national territory on the basis of administrative units (e.g. states, counties, prefectures or communes). This model is used by the state agencies and by researchers (Pick et al., 2001; Postnan et al., 2010; Weidmann et al., 2010; Trincsi et al., 2014; Naveed and Ahmad, 2016; Maystadt et al., 2016). The second

[1] Source of data: Niger Customs, calculation by the author.
[2] Source of data: ACLED.
[3] Smugglers in Niger carry out their activities at night, with exhaust mufflers on their motorbikes, owing to the ban on vehicular traffic in the border zone with Burkina Faso and the curfews that are in place.
[4] The closure of the Lake Chad trade route by the Chadian authorities and the restrictions imposed by Nigeria on the use of fish suspected of being used to raise informal taxes for Boko Haram has resulted in smuggling and widespread suspicion that local officials and members of the military support these informal trade flows in return for bribes (observations gathered during a field mission to Maiduguri, Nigeria, in 2018).
[5] Observations in the Diffa region (November 2018).
[6] Since the two main trade routes through Cameroon and Lake Chad were officially closed in 2016, hauliers travelling from Nigeria to Chad go via the Niger desert; in their words, this is a welcome change because they do not pass any roadblocks set up by the police, the Customs authorities or the gendarmerie along this route. Meeting in N'Djamena in 2016.

model is the grid, which partitions the territory into uniform geometric units (typically squares or hexagons). In the field of conflict studies, the grid was introduced by Buhaug and Rød (2006) and used in global datasets (e.g. the PRIO model by Tollefsen et al. (2012)) before gaining widespread use as a spatial model in security studies (Hegre and Raleigh, 2009; Schutte and Weidman, 2011; Adem et al., 2012; O'Loughin et al., 2012; Weidman, 2013; Besley et al., 2014; Linke et al., 2017; Reeder and Smith, 2019; Curiel et al., 2020; Walther et al., 2021). As far as these two spatial models are concerned, the border zone is the union of the units that are contiguous with the border. Brülhart et al. (2019) form the exception to this rule by demarcating border cells as the union of cells traversed by roads within a limit of 200 km from the border.

There are certain shortcomings in these two models. As regards the administrative model, Agnew (1994) refers to the "territorial trap" of presuming an equivalence between the state and the territory, which derives from a worldview espoused by government officials and military personnel, but not shared by border populations, which are incorporated into the networks and practices of cross-border trade. Armed groups pay no regard to administrative limits of any kind unless they are using them to gain an advantage over the state agencies obliged to respect these highly restrictive confines.

Cell size is an *a priori* decision under the grid model, and an urban or economic unit may therefore be shared between several cells. This problem can be disregarded when investigating natural phenomena, since the urbanization of the spatial unit may be an explanatory variable. For the purposes of a social phenomenon such as armed violence, however, the entirety of a locality must be included in a spatial unit. Data on violence are geolocalized, but this often means that they are assigned to a locality without taking into account the true geographical scope of the conflict outside the geolocalized focus of the incident. The second problem is that each cell in this model has the same neighbourhood. In an irregular tessellation, the neighbourhood of a spatial unit will have approximately the same number of units as in the grid, but they may extend over a different zone in geographical terms (Flache and Hegselmann, 2001). Geographically irregular neighbourhoods are significant when it comes to the spatial analysis of violence, since incidents occur in the neighbourhood of geometrically irregular spatial objects like towns and roads.

This paper addresses the problem of territorial modelling in conflicts and security studies, by proposing a spatial model which takes into account the movements, in particular cross-border movements, and which is intended to be suitable for use not only by security actors, but also for research purposes. On the basis of this model, the paper also develops further the concept of spatial risk analysis, which is still underused by the security forces and Customs authorities in connection with border zone controls. Although these forces control the "border points", a two-dimensional approach to analysing what is happening *between* the border points is absent – with the exception of a very few administrations. In countries with borders that are currently fragile, risk analysis is based not on spatial considerations or systemic approaches, but solely on human intelligence and aerial observations.

The first section of this paper defines the problem of a spatial model on the basis of findings made during field missions to fragile zones and a two-year secondment to the Niger Customs

Administration. The second section explains the construction of a spatial model based on data for localities and data for roads and tracks, using concepts familiar from graphs and spatial networks to build a tessellation of the space on the basis of strategic locations. The third section discusses the possibility that this model could be used for spatial risk analysis, compares it to the other existing models and highlights the benefits of cooperation between the state agencies, based on sharing geolocated data.

Statement of the problem

In technical terms, border security operations can be viewed under three headings: (i) integrating movement – which lies at the heart of the conflict between the state and armed groups – into the partitioning of the territory; (ii) partitioning this space into zones that can be analysed and controlled; and (iii) demarcating the "border space".

Integrating movement into spatial modelling

Border communities are structured around movements: economically in terms of cross-border trade, warehousing and smuggling, socially in terms of leveraging practical knowledge about routes, methods for loading trucks or skills in negotiating with state agents, and symbolically through the values they share with smugglers, who are celebrated as "evaders of the state", or with the local trading elite (Raineri, 2019).

In times of crisis, the transport network is significant for insurgencies (Zhukov, 2012). According to Tollefsen and Buhaug (2015), inaccessibility resulting from a substandard transport network exacerbates the risk of violent intra-state conflicts. The transport network is also a precondition for penetration by the state into the territory. Müller-Crepon et al. (2021) measure the ability of states to access African citizens via the road network, based on the relatively widespread hypothesis that the weaker the state, the higher the probability of conflict (Fearon and Laitin, 2003). While taking fully into account the role of movement in insurgencies, they weigh this accessibility for the state against the fact that internal connections between territories promote movements by armed groups. These movements are all the more important because the groups are fragmented and must band together in order to launch large-scale attacks (Prieto et al., 2020).

From a more economic perspective, former Boko Haram militants have confirmed the importance of markets and transport networks. Prior to 2018, part of Boko Haram's strategy involved carrying out suicide bombings on market days, and using the survivors who returned to their villages as vectors of information and terror in order to "maximize" the political impact of the bombings[7]. These former militants also explained that their groups found it difficult to obtain supplies from local markets without attracting attention. It is better for them to obtain these supplies via intermediaries – typically members of cross-border communities who are known at markets and accustomed to trading venues and practices. Certain militants specialized in trading with these communities, as confirmed by Abba and Dan Dano (2019). A truck driver who was interrogated in Maiduguri (Nigeria) in 2018 after he was kidnapped along with his truck by Boko Haram militants reported his surprise at the expert manner in which they

[7] Interviews of Boko Haram prisoners in a Western Africa state, 2018.

guided him through brushland towards locations where they could hide his vehicle and stash its cargo.

The transport network – including tracks – and the area of influence of the markets associated with this network are both a factor that shapes the border regions from an economic perspective and a political issue with regard to insurgencies and the presence of the state.

As a network of spatial lines, the transport network is therefore insufficient. Firstly, trading centres are clearly necessary to build the spatial model. Secondly, the intermediaries and "stuntmen" (smugglers) in the Sahel have all-terrain vehicles (pick-up trucks, motorbikes) that allow them to follow parallel tracks, sometimes several hundred metres away from the main roads, in order to avoid checkpoints. This is the last crucially important point that must be made as far as spatial modelling is concerned: the main roads and tracks must be incorporated, but their spatial influence outside the "conventional" transport network must also be reflected.

Demarcating the border space

Although sporadic signs are the only visible evidence of borders on the ground, these borders are nevertheless fixed lines for everyone. The same cannot be said for the *border zone*, which each stakeholder interprets individually. Forest rangers divide up the border zone on the basis of environmentally valuable areas and the movements of products extracted from the ecosystem (bushmeat, wood or charcoal). Customs officers view the border as starting at the informal signs along the edge of the road that advertise imported products for sale, and police officers and gendarmes believe that it starts at the passport control points. As far as Customs officers are concerned, the convergence of goods flowing through the bushland towards urban localities and markets is an essential element of their understanding of the territory. For gendarmes or other forces present in more rural areas, moving around the territory and carrying out patrols in villages is an activity that distinguishes them from the police, who tend to operate in more urban areas and control the border points. Military personnel also have their own relationship with the territory. During a field mission in 2020 in a border zone in the Sahel, we noticed that Customs officers had no military backup for their efforts to control smuggling activities in the area surrounding a border village several kilometres from the military post. The military personnel, who were very visible at the top of a small hill alongside the road, explained that they were "holding their post" in order to dissuade jihadists, and were not permitted to leave it. Within a single area, some forces should be stationary and visible with a view to dissuading armed groups, while others should be mobile and engage in covert operations in order to catch smugglers.

Identification of the border zone must take into account the political and technical challenges, namely the importance of movements, i.e. trading centres and transportation routes. For our purposes and at this initial stage, the border zone can therefore be defined as the totality of urban centres and terrestrial transportation routes directly connected to the other side of the border.

This essentially amounts to following the work of the geographer Openshaw, who highlighted the modifiable areal unit problem (MAUP): the way in which we divide space into spatial units influences the outcomes of the analysis. Proposing that we should unshoulder the burden of an impossible objectivity, Openshaw (1983, p. 34) called for a "heresy": "*The selection of areal units, or zoning systems, cannot therefore be separate from, or independent of, the purpose and process of a particular spatial analysis; indeed it must be an integral part of it. This view conflicts with the current use of scientific methods and statistical techniques in geography, and for these reasons many geographers would refuse to consider it to be a viable proposition*." Despite the renown of the MAUP, researchers have paid more attention to the manner in which Openshaw conceptualized the problem (Briant et al., 2008) than to the manner in which he proposed resolving it – by building models that reflect the specific goals pursued.

Partitioning of the national territory – and not necessarily only the border area – is the definition of the spatial model. The tessellation of the territory should make sense according to what we want to analyse, understand and represent, which is, in our case, the movement of goods and people, particularly when crossing borders.

Technical proposition: a spatial model oriented towards cross-border trade

This section describes the main steps followed to build our spatial model, with reference to Niger as an example. The model involves "submersing" the transport network in a Voronoi diagram. The procedure is similar to the concept of a Voronoi diagram for a generalized network (Okabe et al., 2008), which is a tessellation of the space based on a network of points. The concept has previously been applied with a view to partitioning the urban space on the basis of intersections (Yu and Maxfield, 2014), defining urban communities on the basis of the transport network (Yildirimoglu and Kim, 2017) and developing situational pictures of critical infrastructures (Angelini et al., 2015).

The final form of the model's spatial units is therefore based on the transport network and the localities identified as "strategic" in accordance with Hammond (2017), who establishes a link between armed violence and strategic locations within transport networks, i.e. those that are highly connected or those that confer a strategic advantage on armed groups if they are taken (e.g. localities). In our case, the strategic locations are linked to cross-border trade, road junctions and urban or peri-urban localities with markets.

This section describes the six stages involving in constructing the model.

Stage 1: pre-treating the transportation data

The network of roads and tracks lies at the very heart of the model. Choosing and cleaning up these data is therefore critical. Broadly speaking, road data are available from three main sources: public domain projects such as the Global Roads Inventory Project (GRIP) (Nelson et al., 2006; CIESIN, 2013, Meijer et al., 2018), crowdsourced information such as OpenStreetMap, and commercial data.

To the best of our knowledge, there are no recent papers comparing the transportation datasets available for Africa. Only a few major shortcomings have been identified. African roads may be poor in quality, rendering more complex the task of automatic recognition using artificial intelligence tools. Certain roads see little traffic, which means that they are less likely to be identified by crowdsourcing applications. Conversely, certain parts of the national territory are better "connected", with the end result that crowdsourcing applications display a high density of roads or tracks. Ultimately, this point is of secondary importance for our model: indeed, if improved data collection techniques artificially generate a high local density of tracks, this also reflects higher levels of traffic and connectivity, which is, in the end, what our model is seeking to achieve. On the other hand, connection errors are a shortcoming inherent to non-commercial data in general (Ubukawa et al., 2014): two segments of the road appear to be unconnected in the dataset, but are connected in reality. The solution – snapping – can be automated to a certain extent, but a large number of manual adjustments are ultimately necessary.

The identification of all tracks, including potential tracks, is not of critical importance for a spatial model. Conversely, the density of roads and tracks can be a relevant variable for spatial analysis. It follows that these two types of data can be used at different stages. When building the spatial model, the commercial or public datasets, which are less accurate but more homogeneous than OpenStreetMap and contain fewer non-connection errors, can be combined to achieve an acceptable compromise between the quantity of available roads and tracks, their geographical accuracy and the rate of topographical errors. For example, when building our model for Niger, we used the GRIP public dataset, extended by a set of road data developed by GEO212[8]. The two datasets contain few connection errors and complement each other, since the GEO212 set is more comprehensive in desert zones (see Figure 1).

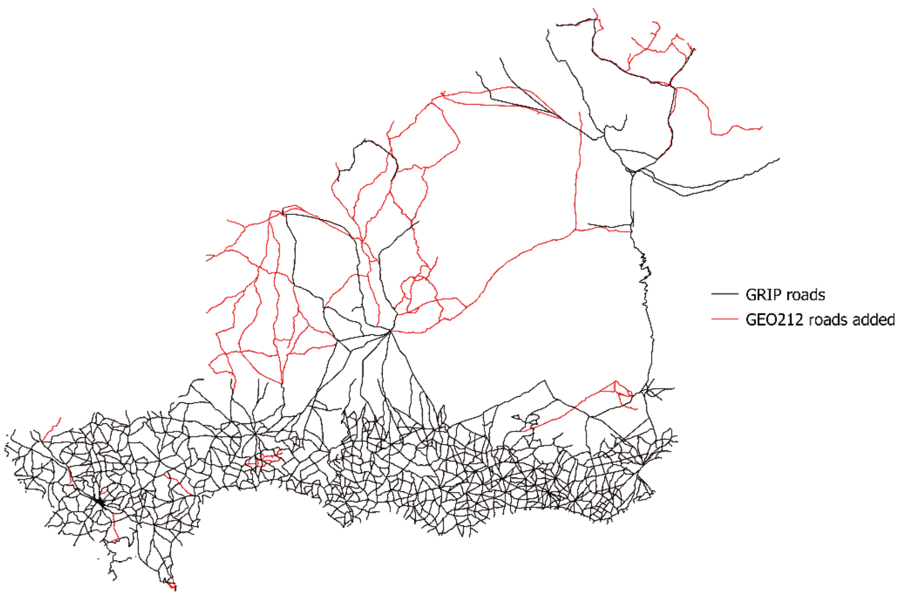


Figure 1. Network of roads and tracks based on two data sets.

A number of pre-treatments were applied to this set: duplicate entries were removed, simplification was carried out (based on a tolerance of 500 metres), each road was divided into

[8] GEO212 company conducted a project with Niger Customs and the World Bank to identify the main cross-border trafficking routes, especially in desert zones.

sections in order to create non-intersecting segments, missing nodes were created at intersections and "snapping" was carried out in order to correct any potential connection errors automatically, based on a tolerance of 500 metres (figure 2[9]). The spatial object *Roads* that was obtained is made up of simple line segments with the following characteristics (table 1).

	Total number of segments	Total kilometres	Length of segments – basic statistics (km)					
			Min.	Q1	Med.	Av.	Q3	Max.
Initial dataset	2,136 (multilines)	52,568	0.0	8.3	16.1	24.6	26.5	865.5
Simplified dataset (tolerance 500 m)	7,764 (lines)	51,968	0.5	3.5	5.7	6.7	8.7	74.2

Table 1. Characteristics of the roads spatial objects before and after treatment.

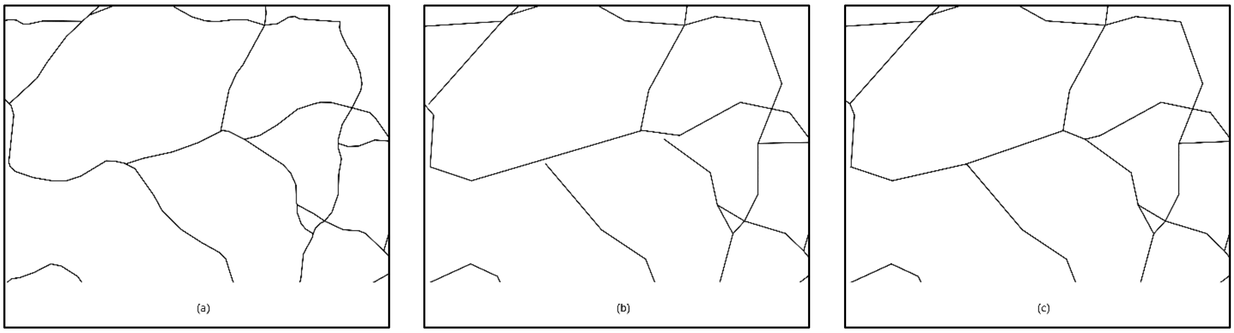


Figure 2. Extract from the road network in Niger, initial (a), simplified (b) and after "snapping" (c). The simplification process decreases the curvature of roads by reducing the number of points through which they pass. "Snapping" makes it possible to re-connect the road segments to each other.

Stage 2: identifying the footprints of localities

Footprints of localities, or in other words polygons rather than points, are necessary in order to ensure that these localities do not straddle multiple spatial units. The Digitize Africa project (CIESIN, 2020) supplies the most comprehensive data available for the footprints of urban localities, villages and hamlets in Africa.

These data must be pre-treated prior to use in our model, with "close" localities combined into a single footprint. Urbanization may also be discontinuous. For example, the footprints of certain localities have "holes" corresponding to the zones that have not been identified by the detection algorithms. What is more, certain distinct localities can be regarded as making up a

[9] The QGIS functions *simplify*, *snap layers, check validity*, *explode* and *intersection* were used when applying these pre-treatments, in view of the speed and simplicity of the process for verifying results visually in QGIS. The simplification method removes vertices from lines. In the process of removing these vertices, simplification may break down relations between road segments that no longer appear to be connected as a result. A "snapping" stage based on the same tolerance then makes it possible to retrieve the initial connections. We then used the R libraries *sf* and *spdep*.

single whole, such as districts that have been "detached" from an urban centre and appear to be separate footprints. Similarly, groups of dwellings in villages may be somewhat further apart than in an urban setting.

After combining footprints at a distance of less than 500 metres from each other, the number of localities in Niger was reduced from 24,599 to 17,028, of which 373 were urban and 16,655 villages. The 296,757 hamlets and encampments identified by Digitize Africa were not used in this modelling exercise.

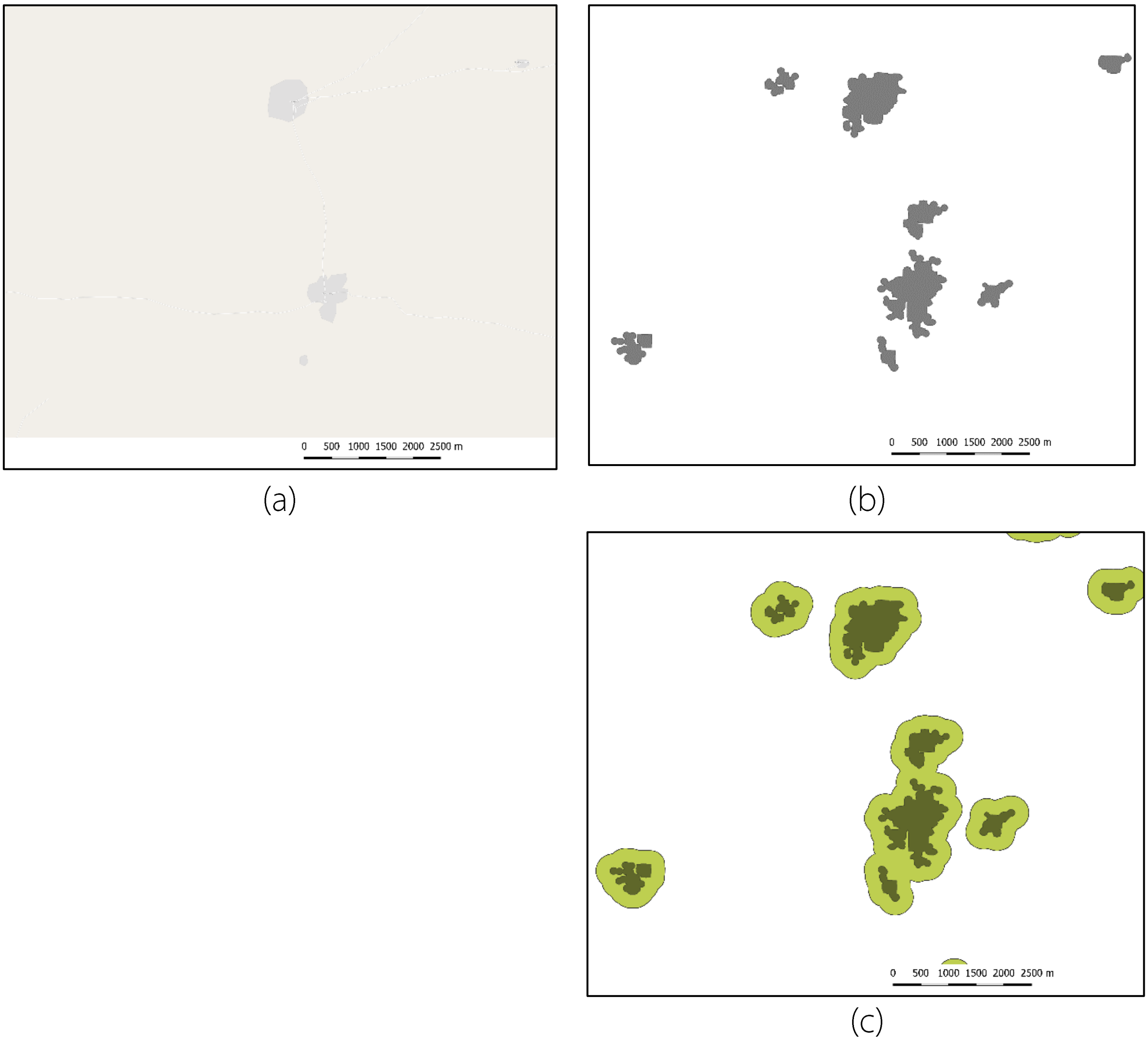


Figure 3. Example of pre-treatment for a zone of villages in Niger on OSM: (a) with footprints from Digitize Africa (b) and treated through the formation of 250-m buffers around the footprints and the union of partially overlapping buffers (c).

	Areas in km²					
	Min.	1st quartile	Median	Mean	3rd quartile	Max.
Before treatment	0.01974	0.11446	0.17439	0.27365	0.28427	181.77376
After treatment	0.3499	0.7197	0.9807	1.4134	1.5272	370.5912

Table 2. Comparison of summary statistics on localities' footprints after and before union treatment.

Stage 3: transforming the road network into a spatial network

The spatial object "roads" is transformed into a spatial network that is a shape enhanced by a graph, i.e. a topological object that does not lose its geographical properties (Barthélemy, 2011; Giabbanelli, 2014).

Graphs are widely used in transport studies, but are also used in security studies as a basis for investigating networks of stakeholders and routes (Sehgal et al., 2018; Hammond, 2018; Walther et al., 2020; Dorff et al., 2020). In our case, the graph models the transport network with nodes (road junctions) linked by edges (road segments). Each edge has a weight equal to the distance in kilometres between the two nodes (along the road). Characteristics relating to movement, such as connectivity and centrality within the network, are assigned to the nodes of the graph. This makes it possible to identify areas that are highly connected to others, or roads that are of critical importance within the network. Graphs are used extensively in network studies, but remain underused for the purpose of actual spatial modelling.

By way of contrast to a simple graph, a spatial network retains the geographical properties of each node (vertex) and edge, namely the longitude and latitude of the point and the set of longitudes and latitudes identifying a line (segment of the road). By assigning the vector of road data to the edges and nodes of the graph in this manner, the spatial network retains not only the connectivity information specific to the graph, but also the geographical information required to produce a spatial model that can be used cartographically.

In our example in Niger, the spatial network is therefore built on the basis of the previous *Roads* network (see Table 3).

Vertices	Total number	Degrees								
		1	2	3	4	5	6	7	8	9
	6,840	278	5250	870	363	54	17	3	2	3

Edges	Total number	Length (m)					
		Min.	1st quartile	Median	Mean	3rd quartile	Max.
	7,638	506	3,563	5,646	6,715	8,630	74,203

Table 3. Characteristics of the spatial network generated by the Roads spatial object.

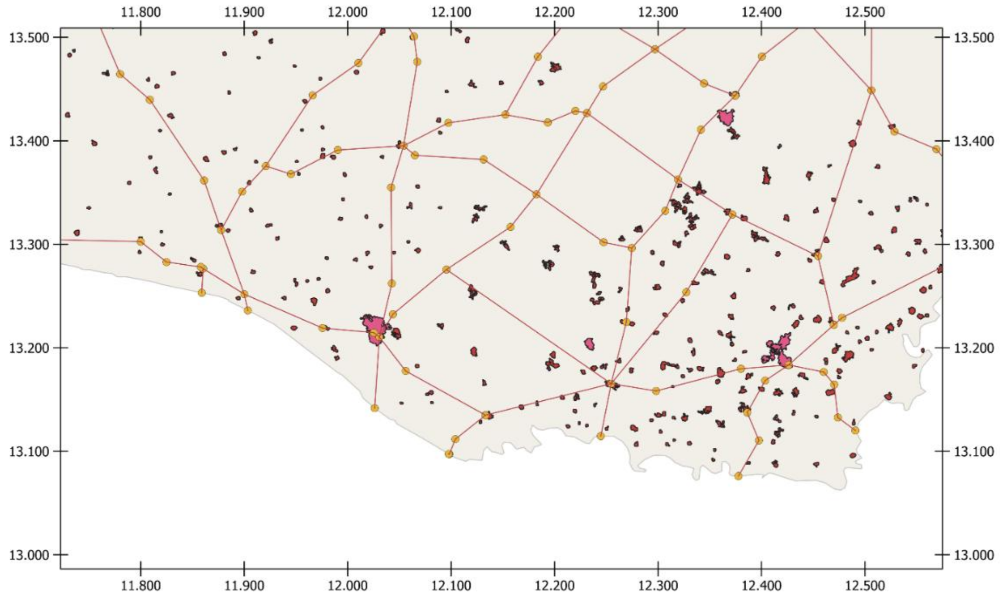


Figure 4. Visualization of the spatial network (edges and nodes) in the Diffa region (11.8°E-12.5°E,13°N-13.5°N) with the footprints of localities.

Stage 4: obtaining a tessellation of the territory using a Voronoi diagram

Voronoi diagrams partition a space geometrically into polygons on the basis of "seeds"; every location within a spatial unit (polygon) is closer to the seed of that spatial unit than to any other seed of another spatial unit.

This tessellation of space is frequently used for operational purposes, such as reconstructing urban or rural zones outside administrative limits (World Bank, 2015), mapping poverty on the basis of the telecommunications network (Steel et al., 2017), optimizing tactical military movements (Chan, 1996), predicting the spread of terrorist activities, incidents of armed violence or the displacement of "hotspots" (Short et al., 2010, Vanderzee, 2018; Lee et al., 2020), aggregating data for the econometric analysis of conflicts (Schutte, 2017) and demarcating zones covered by refugee camps (Jordan, 2017) or territories controlled by armed groups (Tao et al., 2016). In summary, Voronoi diagrams represent either difference or influence: homogeneous spatial units that differ according to one or more factors, or units that are "influence zones" of seeds.

In our model, the complete tessellation of the territory is of the second type; in other words, it is based on the influence zones of the strategic locations that will be seeds in the Voronoi diagram. Hammond (2017) has highlighted the correlation between armed incidents and locations that are of strategic interest but lack direct economic value. We define "strategic" nodes and localities in keeping with our model, i.e. using a dual approach (the properties of the graph and the geographical properties of the localities), depending on whether flows converge towards these locations or not:

– nodes with a degree greater than or equal to 3 and the localities that contain them;

– urban localities or "large" villages not containing a node with a degree greater than or equal to 3 and the nodes that contain them, since these localities may potentially be the site of markets.

The category "urban" follows the definition given by Digitize Africa. As a first approximation, we define the category "large villages" as villages whose footprint is greater than or equal to the median of footprints for urban localities. This approximation was discussed with reference to the example of strategic villages provided by Customs authorities in Niger.

An operational constraint has also been imposed for cartographical purposes: the tessellation must be sufficiently accurate to follow the boundaries of strategic locations (no strategic location may straddle multiple spatial units) and roads. We follow the algorithm in Annex 1 to build the raw tessellation, then gradually aggregate spatial units in order to end up with an operational tessellation.

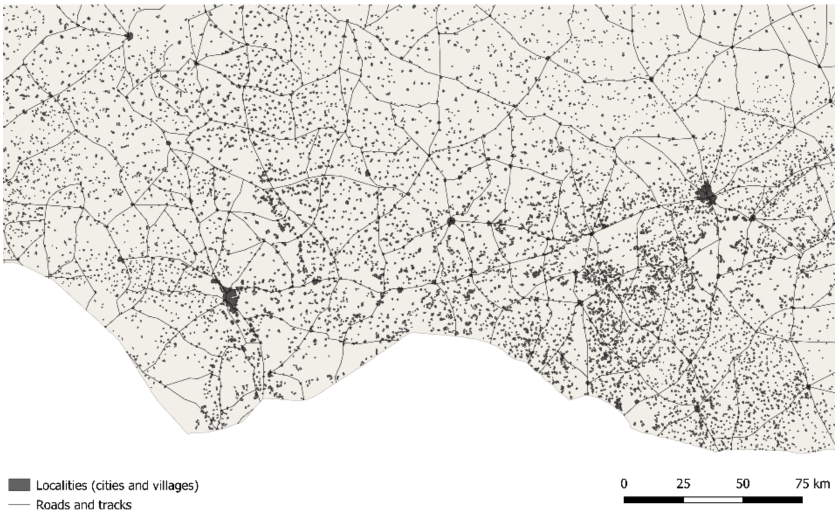
The algorithm delivers the following results for Niger.

Nodes	6,840
…strategic	1,562
……degree >= 3	1,312
……degree < 3 and in urban localities	162
……degree <3 and in large villages	88
Localities (after pre-treatment)	17,018
…strategic	1,611
……urban	373
……large villages	431
……neither urban nor large villages but containing a node whose degree >= 3	807
Seeds	24,938
Seeds 1: strategic nodes in localities	1,205
Seeds 2: strategic nodes outside localities	357
Seeds 3: sampling points into strategic localities	17,098
Seeds 4: non-strategic nodes	5,278

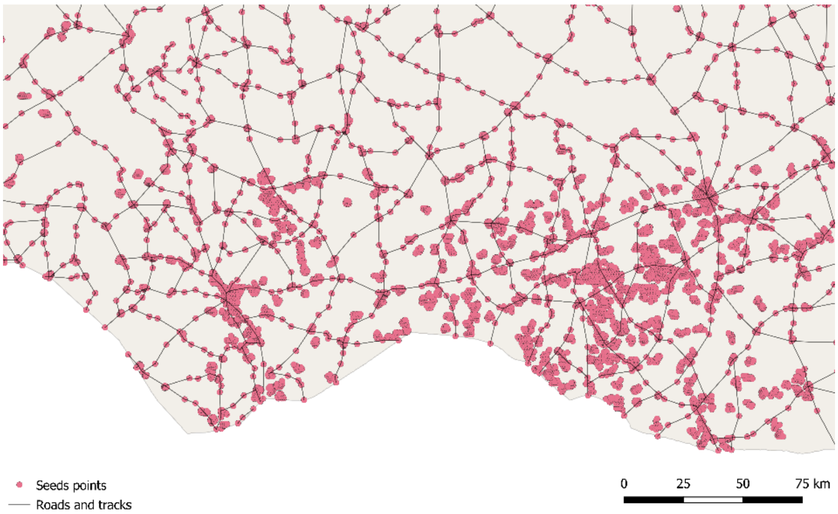
Table 4. Strategic locations in Niger, seeds for Voronoi diagram and polygons.

The first point worth noting is the high proportion of small villages that are intersections of permanent tracks: this provides an *a posteriori* justification for the hierarchical order prioritising nodes with a degree greater than three. The second point to note is that, despite the high number of seeds sampled in strategic localities, their preponderance does not affect the tessellation: since they are concentrated within footprints of localities, they merely ensure that the tessellation is consistent with the footprints.

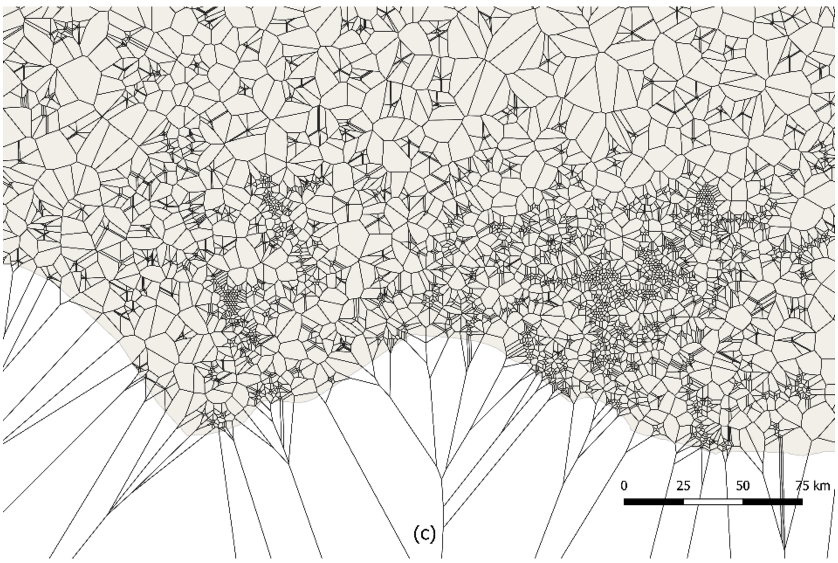
Following application of the tessellation algorithm, we obtain the results shown below for Niger (figure 5).


Localities (cities and villages)
Roads and tracks
0 25 50 75 km

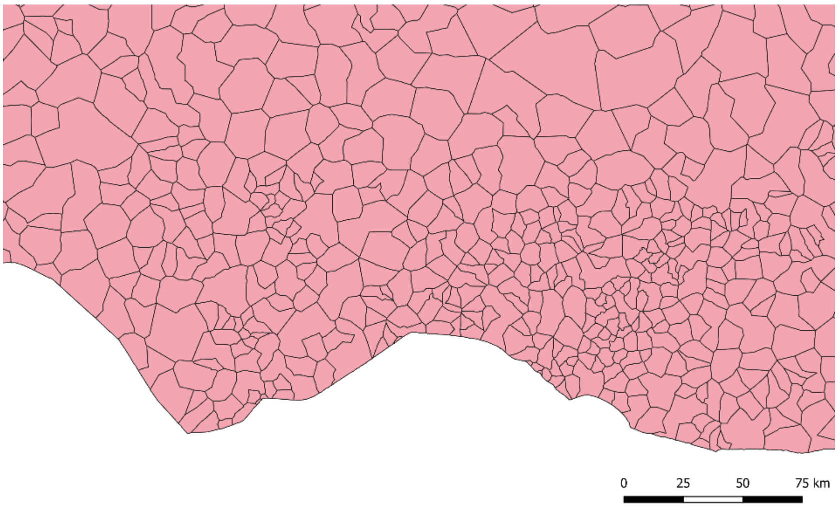
(a)


Seeds points
Roads and tracks
0 25 50 75 km

(b)


0 25 50 75 km

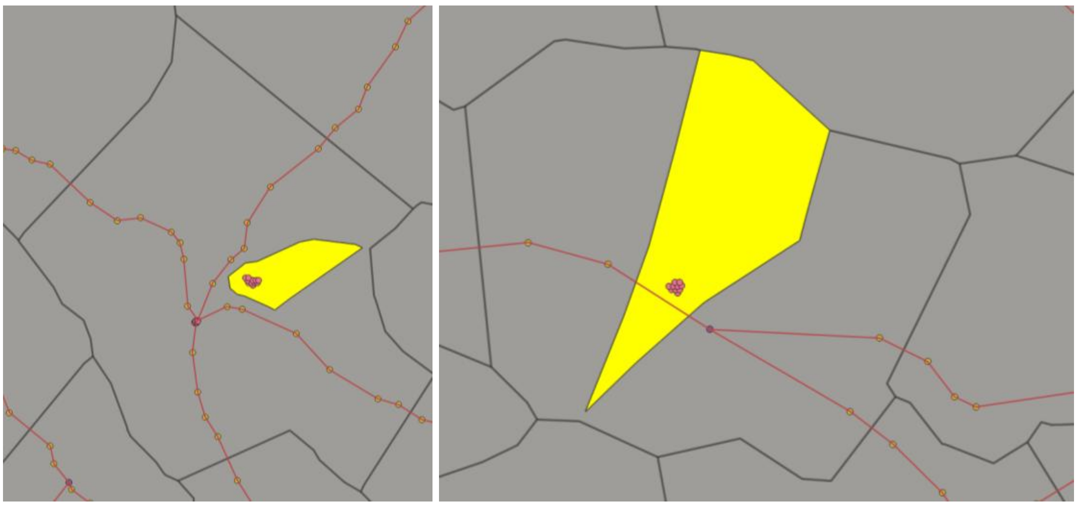
(c)



(d)

Figure 5. Illustration of the tessellation process using the example of a zone in Niger (region around Zinder) (a); the process involves transformation into seeds with a concentration of seeds in the strategic towns and villages (b), followed by elementary tessellation (c) and then aggregation by connection key (d).

Initial post-treatment improves the tessellation that has been obtained by treating "isolated" or "quasi isolated" polygons (Figure 6).



(a) (b)

Figure 6. Polygons "inside" other polygons due to the presence of seeds. Case (a): isolated polygon (polygon within another polygon, having only a single neighbour). Case (b): quasi-isolated polygons (polygon having only two neighbours and therefore effectively within a polygon). These polygons are detected and merged into the polygon they are inside.

In these two cases, localities have been categorized as strategic because of their size, but are outside the road network that has been identified or merely have a road passing through them;

however, they are close to a strategic node of greater importance (junction, strategic locality with road junctions) whose influence "surrounds" the locality in question.

The solution that was chosen involves looking again at the road network and potentially carrying out corrections; if the isolated locality is linked by permanent tracks appearing in the public data (satellite images from Google and Bing and OSM data), we modify the initial set of *ROADS* data. If no permanent track appears in this data, the isolated or quasi-isolated spatial unit is merged with the spatial unit that contains it (case (a)) or the spatial unit with which it shares the longest border (case (b)).

Since the objective is to obtain spatial units that can be analysed and controlled, a second post-treatment associates the smallest spatial units with the smallest neighbouring units in order to obtain spatial units whose surface area is above a certain threshold, for example 25 or 100 km^2, which corresponds to the daily range of a patrol and an in-depth visual assessment of social imaging (Figures 7 and 8). Table 7 reports the statistics of the tessellation at different steps and after post-treatments.

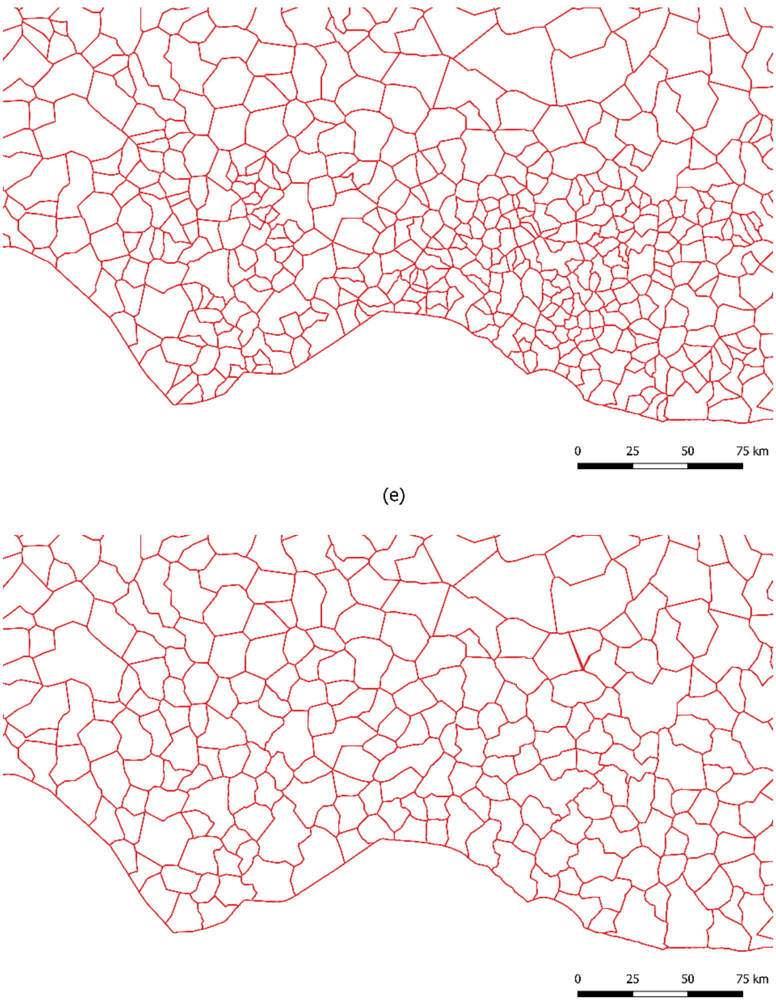


Figure 7. Transformation into units with a minimum surface area of 25 km^2 (e) or 100 km^2 (f).

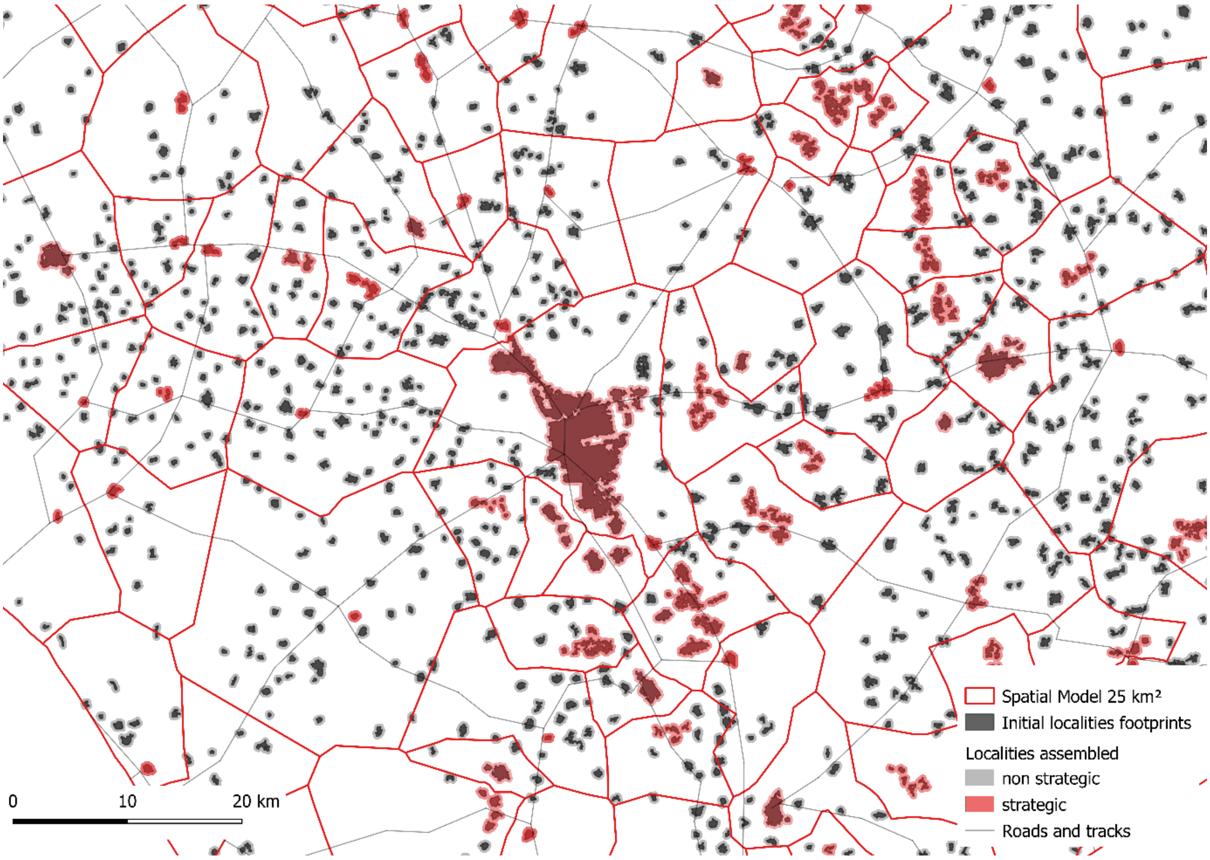


Figure 8. Illustrates the process of tessellation on the basis of roads and tracks (Stages 1 and 3), footprints of localities, the grouping of localities by proximity (Stage 2) and a distinction between strategic/non-strategic localities (Stage 4) in the zone of Maradi (Niger).

Polygons directly issued by the Voronoi diagram							23,900
Polygons after aggregation by connection key							2,097
Polygons after post-treatment of merging isolated or quasi-isolated polygons							2,044
	Summary statistics of polygon areas (km^2)						
	Min.	Q1	Median	Mean	Q3	Max.	
	0.2	60.1	125.5	587.2	292.8	48,298.5	
Polygons after post-treatment of minimal area 25 km^2							1,940
	Summary statistics of polygon areas (km^2)						
	Min.	Q1	Median	Mean	Q3	Max.	
	25.0	68.4	138.6	618.6	304.1	48,298.5	
Polygons after post-treatment of minimal area 100 km^2							1,303
	Summary statistics of polygon areas (km^2)						
	Min.	Q1	Median	Mean	Q3	Max.	
	100.2	169.8	269.1	921.1	458.0	48,298.5	

Table 5. Basic statistics for tessellation.

Stage 5: identifying border zones

Within the spatial network, all cross-border points are identified as nodes at the intersection of the road network and the border line (where the road crosses the border) and nodes within a strip of 500 metres from the border line, with a view to correcting any errors in the dataset for the road network (incomplete segments of an incomplete cross-border road).

Nodes inside strategic localities (and which therefore have a market) are identified within the spatial network. The model calculates the shortest path from each cross-border node to a strategic locality. The urban localities that are connected to a cross-border node are characterized as "trade hubs", as well as the roads that link these localities to their cross-border nodes.

The border zone is thus identified as the union of spatial units that are crossed by roads used for cross-border trade, or that contain a trade hub locality (Table 6).

Cross-border roads and tracks	550 for 8,388 km
Cross-border nodes	655
Localities cross-border trade hubs (final destinations of cross-border roads and tracks)	148

	Spatial model 25 km²	Spatial model 100 km²
Spatial units in borderlands	400 (21% of spatial units)	268 (21% of spatial units)
Localities in borderlands	3,694	3,937
Total area of borderlands	503,000 km²	505,000 km²

Table 6. Features of the borderlands provided by the spatial model.

Outcomes and discussion

Comparison with other spatial models

From a conceptual point of view, the tessellation obtained on the basis of our model responds to the challenges raised in introduction and section 1 ,compared to the administrative and grid models: more irregular and thus more readily able to accommodate spatial interactions and more faithful to the human geography of zones, without being based on either *a priori* naturalistic concepts (where the territory is divided into regular squares) or *a priori* historical concepts (where the territory is divided according to the history of relations between localities). The *a priori* concept explicitly underpinning the spatial model is movement.

Basic statistics describing our spatial model, at different scales (minimum area of 10, 25 and 100 km^2) and other spatial models are summarized in table 7 for Niger. These statistics include a granularity index defined by Sadahiro (2010) for tessellations. This index is the sum of the square of the surface areas of the polygons in the tessellation divided by the square of the surface area of the entire region. The Figure 9 provides a basic visualisation of the different spatial models in Niger.

The statistics show that our model is consistent in terms of borderlands: whatever the minimum ceiling for units' areas, the delineation of borderlands does not vary much. The granularity of our model is better than the one of the administrative model. In substance, this means that the administrative models based on the division of territory into administrative units offer less opportunities for spatial analysis. Furthermore, our model is more homogeneous than the administrative models in terms of the surface area of spatial units.

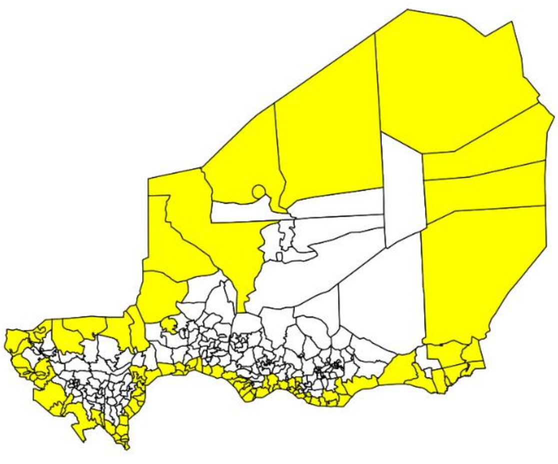
Compared to the grid model, the surface of the borderlands in our model is a bit higher, which is normal: the grid units are uniform and do not take into account the extension of the desert areas. The same comment applies for the granularity of the model that is better for the grid than for our model. In fact, our model offers a lower share of areal units as part of the borderlands, which, in the end, reduces the number of localities in the borderlands.

Although it does not qualify as a spatial modelling method per se, the "border strip" (covering a fixed distance of between 15 and 50 km) is also represented, as it is often used to assess insecurity "at the borders" (O'Loughin et al., 2010; Ali et al., 2018; Walther, 2019; Radil et al., 2022). It is not a spatial model in and of itself, but it is used in spatial econometry models as a Boolean variable to identify factors of violence). It is not unsuitable for operational purposes that require more detailed analyses. Furthermore, a fixed distance prevents any efforts to take into account the influence of terrain on human activities. In desert settings, for example, trade flows shape human geography a long way into the national territory. In Niger, the 50 km border strip does not incorporate locations such as Dirkou or Arlit, which are located over 200 km from the border. Similar observations hold true for the north of Mali or Chad, and more generally for all of the "Saharan" towns that form an age-old trading network around the Sahara (Pliez, 2011). The finding can also be applied to mountain settings where the altitude represents a further factor of remoteness, in addition to linear distance from the border.

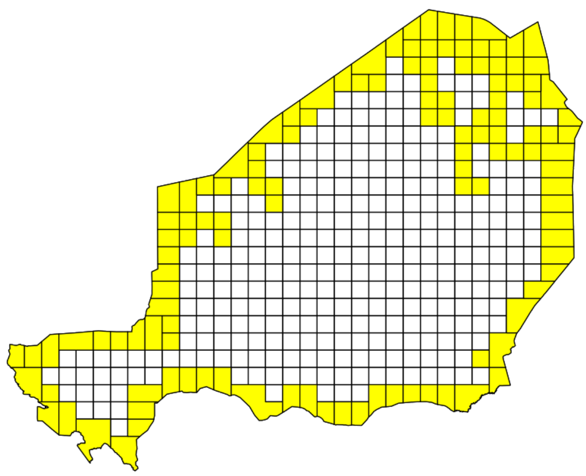
The spatial models have been applied to Mali, Burkina Faso and Nigeria, with similar results.

Niger						
SPATIAL MODELS	Buffer 50kms	Admin.[10]	Grid 50kmsx50kms	Spatial100	Spatial25	Spatial10
National territory						
number of spatial units		266	434	1,300	1,940	2,028
minimum area (km^2)		10	2,500	100	25	11
first quartile area (km^2)		397	2,500	170	68	61
median area (km^2)		792	2,500	269	139	127
mean area (km^2)		4,153	2,767	921	618	592
third quartile area (km^2)		1,767	8,533	458	304	294
maximum area (km^2)		160,178	…	48,298	48,298	48,298
area standard deviation		16,368	788	3,386	2,806	2,748
Sadahiro Granularity Index		0.053	0.002	0.011	0.011	0.011
Borderlands						
number of spatial units	1	92 (35%)	126 (29%)	268 (21%)	400 (21%)	415 (20%)
borderlands area (km^2)	254,641 (21%)	770,379 (64%)	430,697 (36%)	505,000 (42%)	503,000 (42%)	503,000 (42%)
number of localities	7,033	6,496	8,040	3,937	3,694	3,686
…among which are urban	150	130	188	75	70	69

Table 7. Comparison of spatial models.

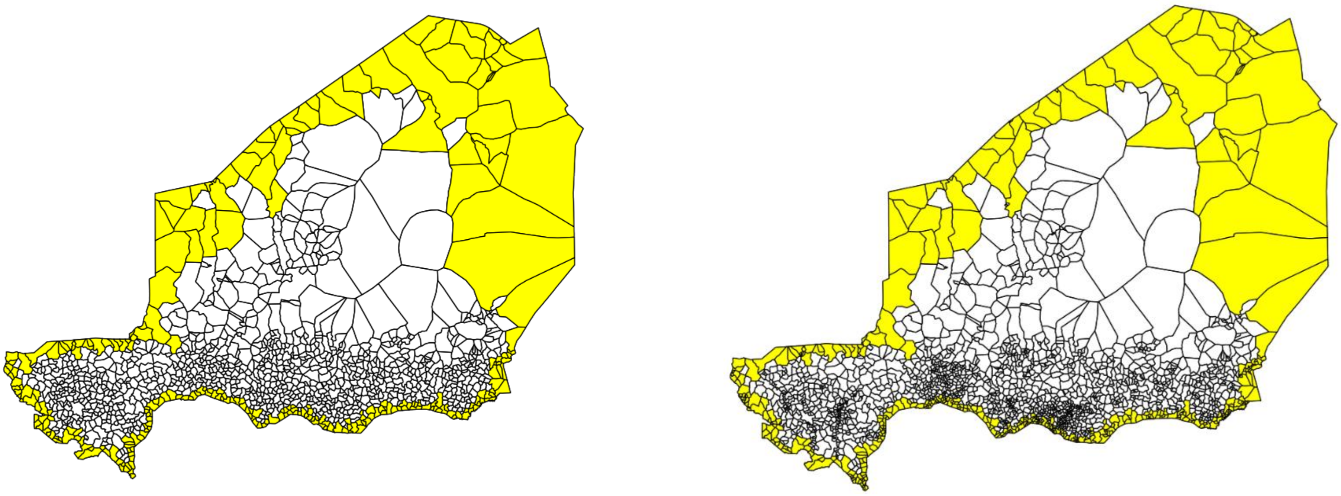


(a)



(b)

[10] Source: OCHA (https://data.humdata.org), administrative level is "commune".



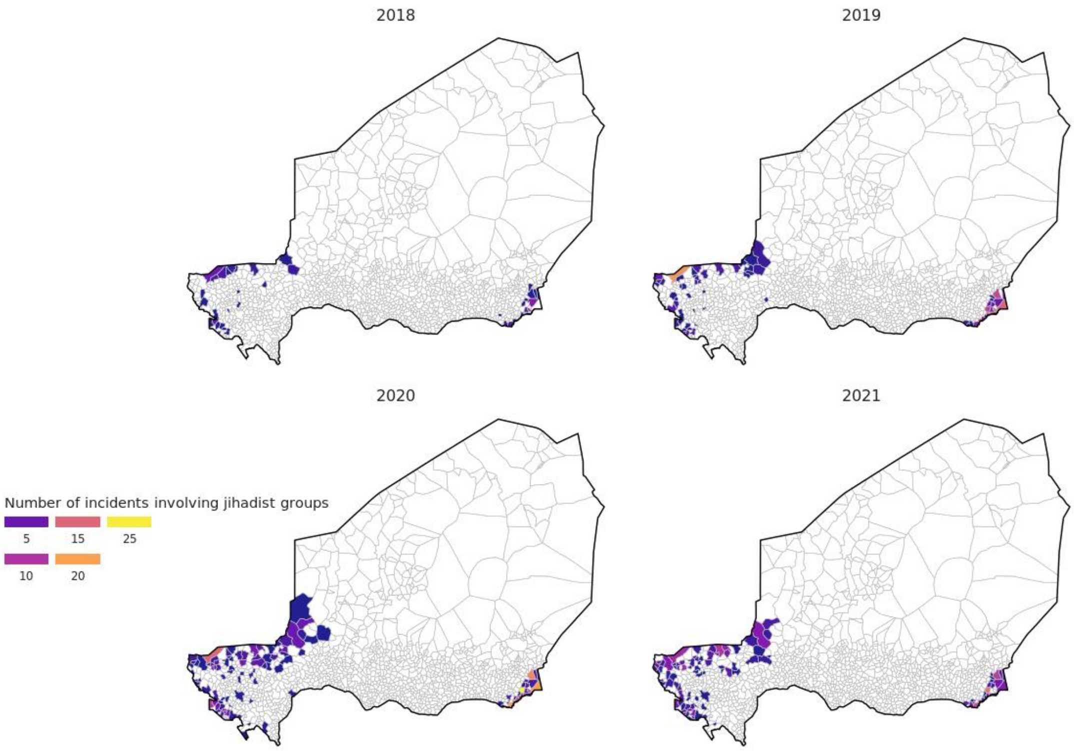
(c) (d)

Figure 9. Different spatial models and borderlands (yellow): administrative model (a), grid 50kmsx50kms (b), our model with minimum area ceiling 100 km² (c), our model with minimum area ceiling 10 km² (d).

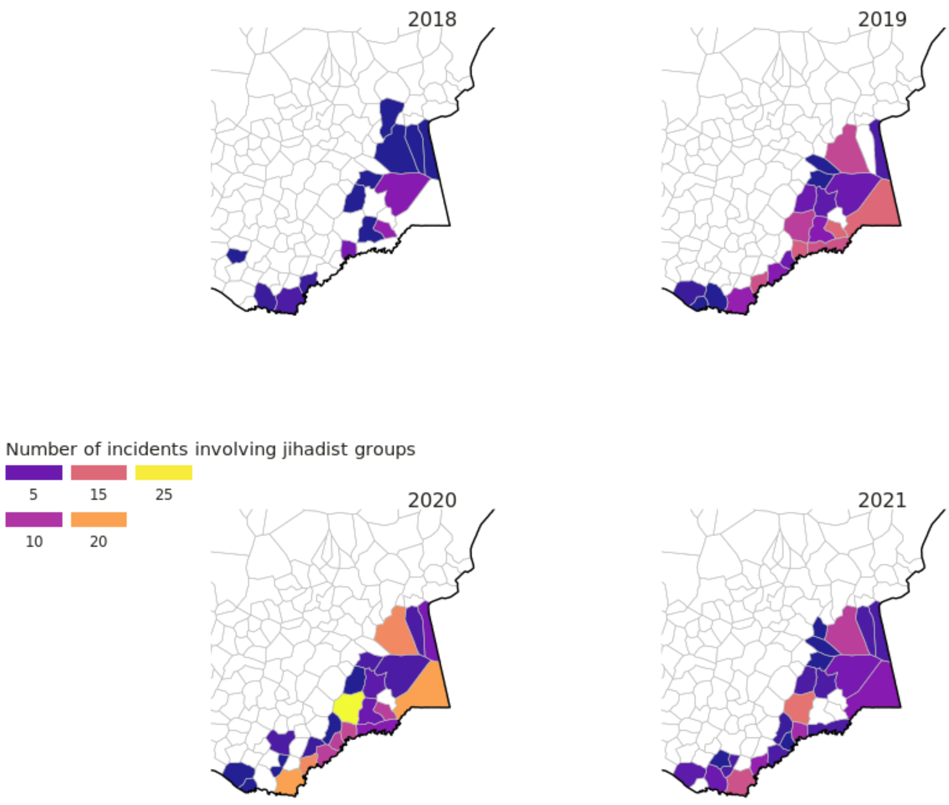
Use of the model for spatial risk analysis

Three types of spatial risk analysis can be carried out on the basis of this spatial model in pursuit of the primary objective discussed at the start of the paper, i.e. gaining a better understanding of the interrelationships between security and economy at the border with a view to improved management of the latter.

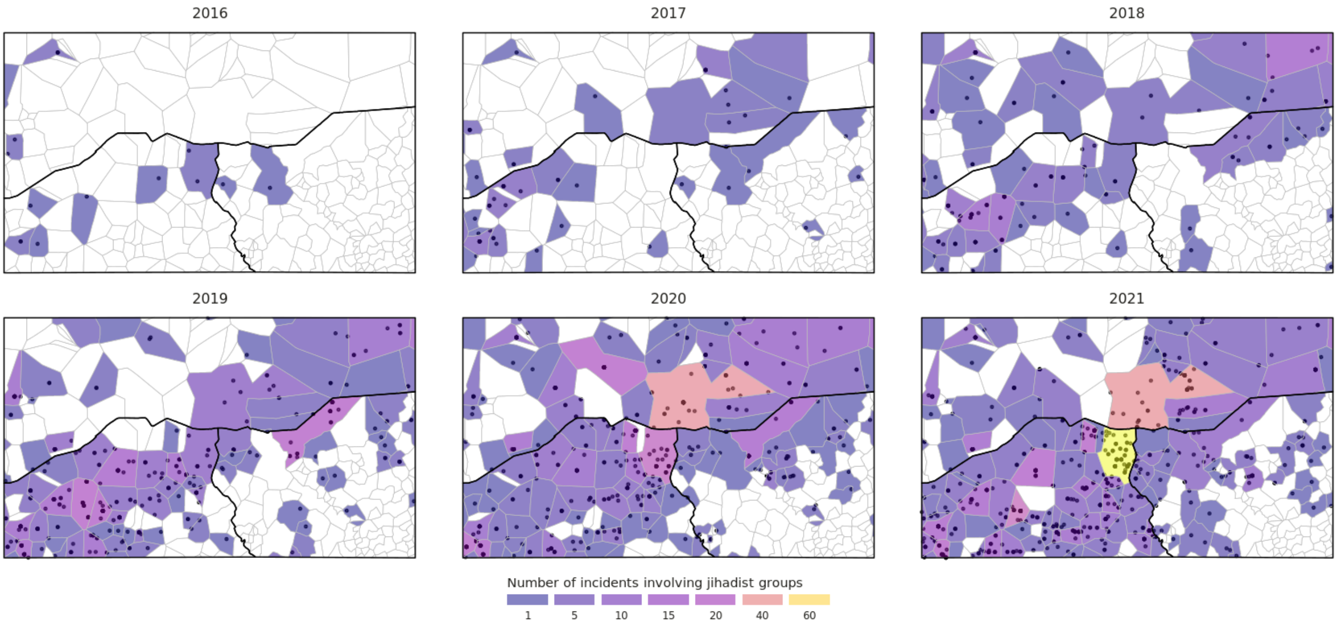
The first is analysis of the security risk based on the production of a borderland situational picture of armed incidents. Data on armed incidents originate from a public database on geolocalized incidents entitled Armed Conflict Location & Event Data Project (ACLED) (Raleigh et al., 2010). The granularity of the spatial models allows operational analysis of the dynamics of insurgencies (see Figure 9). Situational pictures are in widespread use in security-related fields with a view to fusing information, data and information in an institutionalized and automatic manner (Llinas, 2013). In Niger, some situational pictures have been issued, combining the evolution of incidents and the evolution of revenue collection within the same borderland.


2018
2019
2020
2021
Number of incidents involving jihadist groups
5
15
25
10
20

(a)


2018
2019
Number of incidents involving jihadist groups
5
15
25
10
20
2020
2021

(b)



(c)

Figure 10. Examples of situational pictures at different scales, national territory (a), regional in the Niger Diffa area (b) and in the "zone of 3 borders" between Mali, Burkina Faso and Niger (c).

We tested the analysis of hotspots (spatial clustering) as used in the cartography of criminality, which is a field of study with similarities to our context (Anselin, 2000; Law et al., 2020). This approach is appropriate in urban zones where criminal acts are localized and easily identified, or in other words in environments where movements are significantly constrained by the topography (street, buildings). Hotspot-based analysis of this kind has proven to be of little value in our context, however. Incidents such as kinetic attacks may occur over vast areas, and it is therefore impossible to localize them at a single point. Furthermore, the information on jihadist operational areas delivered by hotspot analysis is not detailed enough, and is already familiar to field practitioners. The tessellation of the territory into spatial units allows improved operational understanding of territorial security in both time and space.

The second type of risk analysis is economic in nature, and involves the identification of areas where smuggling may occur based on the presence of cross-border roads and tracks. These roads and tracks may be familiar to Customs officers, but – to the best of our knowledge, based on the 20 or more countries we have visited – have never been visualized cartographically. What is more, it is a challenging task for security forces to categorize these roads and tracks according to their level of risk, even though this is necessary for on-the-ground decisions about the location of patrols and temporary roadblocks (or "ambushes", to use the terminology of Customs officers in the Sahel). Finally, it goes without saying that controlling potential transit points is impossible (the model identified 655 points in Niger, for example), all the more so because these points are in reality "zones" since each transit point is surrounded by a large number of tracks. The strategy adopted by Customs officers and security forces involves carrying out controls in urban centres of consumption, or in other words on the outskirts of large towns. However, before re-selling their goods, smugglers store them in villages located in the border zones and dispose of them gradually, thwarting any attempts to carry out controls over large areas. In addition, some of the smuggled goods are also sold in villages straight from warehouses in the bushland, without necessarily passing through urban centres.

The spatial model has provided three types of added value for Customs services. The first is the identification of transit points, i.e. preferred cross-border roads and tracks, as a basis for visualizing them on a map and sharing this information within the local Customs services and with the other security forces. The second added value is the identification of villages located within the border zone at the meeting point of multiple cross-border routes, since these villages may serve as a basis for more accurate controls than urban centres alone. The third type of added value is the linking of spatial analysis to the analysis of very high-resolution satellite images. The data generated using this model were used as the basis for a study carried out with the European Space Agency in order to assess the economic development (number of new homes, buildings and corrugated iron roofs[11]) of around 30 villages in a border zone between Niger and Nigeria, located in the vicinity of preferred cross-border routes (as defined under the model) and not known to Customs services. Customs services were provided with detailed information on around 10 border villages or hamlets that had expanded rapidly over recent years.

This use of the data for economic purposes – to detect smuggling – could be improved by assigning three risk indices to each spatial polygon: a friction index on the basis of land cover, a population density index (villages, hamlets, encampments) to identify non-urban zones that may potentially be used for purposes relating to informal cross-border trade (i.e. to store goods or to find consumers), and a track density index[12].

The third use combines the principles of other two, by aiming to identify zones that are suspect from a security and economic perspective, or in other words zones where armed incidents do not prevent economic development. In the context of economic relations – forced or voluntary – between armed groups and cross-border communities (as described in Section 1), we reversed the hotspot method used by the police (based on the cartography of criminality) and instead searched for zones of peace and economic development in the midst of zones of violence. "Suspect" does not automatically mean that the target localities shelter jihadist groups;

[11] The number of corrugated iron roofs in a village is a variable often used by economists to estimate economic development in rural settings (Vashney et al., 2015); nowadays, it is probably used more widely than time series of night-time lights thanks to the democratization of high- and very high-resolution satellite images.

[12] These improvements are outside the scope of this paper, which focuses on spatial modelling. Data exist and have been tested for these three types of indices. Land cover data for Africa have been made available by the European Space Agency (https://2016africalandcover20m.esrin.esa.int). Testing these data has proven to be a complex task, however, since land cover in many border regions in Niger also varies depending on the season. Population densities can be approximated using global geolocalized data or, using data from Digitize Africa, by calculating the density of footprints for localities including hamlets (not used for our spatial model) per spatial unit. In the case of tracks, the density of tracks per spatial unit can similarly be calculated using OSM data, which are more comprehensive but were not used in our spatial model owing to the high number of connection errors.

they may also be the site of a recent military or refugee camp that has attracted displaced persons. We have defined a spatial unit as suspect if it is free from armed incidents and the majority of neighbouring spatial units have been the site of armed incidents. Our chosen time scale is of an appropriate length for economic development, or in other words six months.

The suspect units are then analysed visually using very high-resolution satellite images in order to identify the precise locations where suspect activities are expanding, based on clues such as the presence of warehouses.

The use of satellite images to detect smuggling zones is not a novel concept. Pinto et al. (2018) used images of this kind to detect cross-border transit points and smuggling routes in inaccessible tropical forest areas in Brazil. Yet, although VHR satellite images are an essential tool for obtaining visuals of areas that are difficult to access on the ground (either due to security risks or because of the need to remain discreet), they are equally a tool that can be used at the end of the process in order to manage the borders. Border zones extend over large areas, and economic development takes place over large time scales. The use of VHR satellite images is thus impossible in the first instance.

Spatial risk analysis is therefore based on a funnel approach, combining the use of data on incidents, human intelligence, specific spatial factors and the detection of changes, all within the framework of the spatial model (Figure 11). The aim is to pinpoint locations as accurately as possible before satellite images are used, in order to decide where interventions should take place and prepare for operations.

This funnel model has been tested over the entirety of a suspect zone. The model identified suspect zones, and a specialist entity (the EU's Satellite Centre, SatCen) produced an analysis of cross-border transit points and suspect localities, which was used as a basis for operational controls in the field. In 2021, a Niger Customs unit leader used this analysis of suspect areas to complement human intelligence on a potential fraud organized from a coastal country. After estimating that the goods had been smuggled into Niger and remained stored in the border area, he used the maps and images of the suspect areas issued to estimate the potential storage village for the goods, in relation to its development in recent months as an "active" smuggling village. This allowed the intervention team to find and seize the goods while spending less time in the insecure area, thus limiting the risks of exposure to jihadist groups.

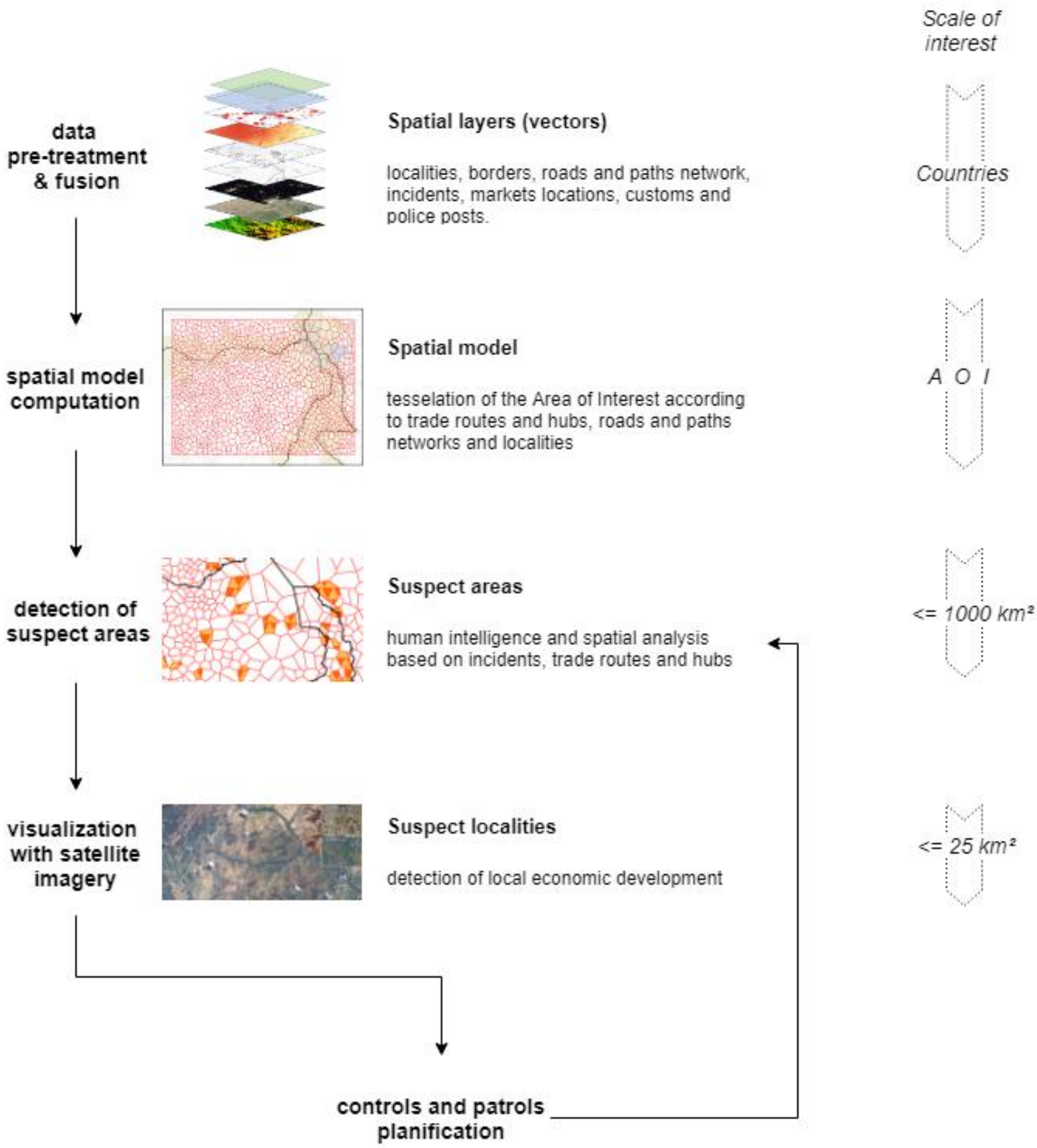


Figure 11. Scheme of spatial risk analysis for border control objectives.

Conclusion

Over a period of many years, the border and the border zone have morphed into concepts that are sometimes more cultural than geographical. Borders are de-localized with a view to obtaining new re-definitions of communities on the basis of cultural links and mobility (Alvarez, 1995; Thiemann et al., 2010; Donnan and Wilson, 2021). Yet, on the ground, for inhabitants under threat from armed groups and under surveillance by state agencies, the border is a harsh reality.

When we "see like a state" (Scott, 1998), there are no longer any empty areas or "white spaces", to use the term coined in the 19th century to describe sections of a map where no symbols appear. Theoretically, it is no longer possible to leave a governed area without entering another governed zone. In the Sahel, however, new white spaces are appearing along the borders, which serve as the backdrop for violent confrontations between state and non-state actors. When the state falters at its borders, movements of goods continue or even increase in scale, because these movements have historically been the main economic activity engaged in by the border populations which are nowadays subject to insecurity.

Given the geographical scale of the problems, any technical solution relies on cooperation from state forces. Although this cooperation lies at the heart of discourses and projects by national and international stakeholders (Directorate for Security and Defence Cooperation, 2015; G5 Sahel, 2015, 2016, 2020; Council of the European Union, 2015, 2019), it remains difficult to achieve owing to factors such as mistrust stemming from suspicions of corruption[13], siloed attitudes, hesitancy to share authority or an office[14], a lack of formalized procedures[15], or a preference by landlords for one agency over another (Brachet, 2016; Jackson, 2018; Claes et al., 2020[16]).

Gaining their cooperation at the border presupposes that they *share* the same space, and thus in particular that they share the same conceptualization of the border space. Maps in a broader sense are a tried-and-tested tool for cooperation between the security forces, based on experiences with COMPSTAT in the United States (Willis et al. 2007, Nuth, 2008). Geographic information systems are at the core of the US federal agencies' concept of information fusion[17], for example. The European Border and Coast Guard Agency (Frontex) also uses maps and geospatial technologies to supply the EU Member States with a picture of the situation at the borders and the available information, *inter alia* with a view to supporting cooperation between the Member States and optimising the deployment of resources (Malinowski, 2019).

But, technology is not enough. Ensuring or restoring the presence of the state in borderlands under jihadist threat means acting as state representatives, in the name of a shared political cause. This shared political cause should also be technically definable, which is, in the case of Sahel, enabling the state forces to control the border without preventing the functioning of its economy and without creating a disincentive for populations to support the

[13] Arguments heard repeatedly during field interviews with Customs officials and police officers in three Sahel countries between 2018 and 2021.
[14] Meeting with a European police officer working on a joint police/Customs project in a Sahel country (June 2020).
[15] During a joint operation organized by two Sahel countries, the Customs administrations simply exchanged zoning maps and details of the parties responsible for each zone; no "shared map" was produced (observation on the ground, 2020).
[16] At a border point where representatives of both the police and Customs were present, we observed that the members of the police had access to a power supply but the Customs officers did not; according to the member of the police responsible for coordinating these projects, this was a result of "tendering formalities" (meeting in September 2019 in a Sahel country followed by observations at the border point in question, which has since been destroyed by an armed group).
[17] See the reference document published by the US Department of Homeland Security/Department of Justice on fusion centres:
https://bja.ojp.gov/sites/g/files/xyckuh186/files/media/document/defining_fusion_center_technology_business_processes_a_tool_for_planning.pdf

state. Spatial risk analysis entails a spatial model that is sufficiently detailed to identify suspect zones and target control resources on the basis of economic risk (smuggling) and security risk (armed groups).

Restoration of the state, whether for development or security purposes, presupposes knowledge of the priority areas for such restoration efforts, taking into account the geographical and social scale of insurgencies, the limited nature of resources and the need to allow all stakeholders in the crisis resolution process to state what is actually of significance to their departments or communities. Spatial models are nothing more than containers for political conceptions of the world. There is no map in existence that can put an end to insurgencies, but it will be difficult to put an end to insurgencies without a map.

Data availability: the author confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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