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Understanding transportation-caused rangeland damage in Mongolia

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ABSTRACT

Mongolia, a vast and sparsely populated semi-arid country, has very little formal road infrastructure. Since the 1990s, private ownership and usage of vehicles has been increasing, which has created a web of dirt track corridors due to the communal land tenure and unobstructed terrain, with some of these corridors reaching over 4 km in width. This practice aids wind- and water-aided erosion and desertification, causing enormous negative environmental effects. Little is being done to counter the phenomenon, mainly because the logic of the driving behaviour that causes this dirt road widening is not fully understood.

The research in this article postulates that this driving behaviour has rational foundations and is linked to various geographical factors (natural and man-made geographical features). We analysed 11,000 km of arterial routes in the country using spatial statistics and determined that geographically weighted regression (GWR) analysis offers a good explanation for whether, and by how much, the selected geographical factors affect the creation of corridor widths and how their effect varies across the landscape.

We determined that corridor widths are correlated to factors such as proximity to river crossings, traffic intensity, and vegetation abundance. Knowing these factors can help local planners and engineers design counter-measures that could help to control and reduce the widths of these corridors, until paved roads can replace the dirt track corridors.

1. Introduction

It is a commonly accepted paradigm that asphalted roads result in damage to the environment (Clevenger et al., 2003; Forman, 2003; Poteete, 2012; Roedenbeck et al., 2007). However, in rangelands such as those of Mongolia, the scarcity of proper road infrastructure also damages the environment because of unregulated driving. The passage of wheels compresses the grassland, not only killing the vegetation but also compacting the ground and damaging its ability to absorb and retain moisture and nutrients (Belnap, 2002; Dregne, 1983) and thus causing land degradation because of soil compaction, crusting and sealing (Arts et al., 2012; Gubbi et al., 2012). In doing so, the flow characteristics of surface water run-off is concentrated and magnified, thus leading to soil erosion and increased sediment loads in water courses and stream networks (Malczewski and Jelokhani-Niaraki, 2012), which is damaging to aquatic habitats and water quality (Misak et al., 2002). Using carbon, nitrogen, porosity and hardness of the top layers of the Mongolian soil, Li et al. (2006) noted that re-vegetation of such damaged vehicle tracks requires approximately 10–15 years after the track has ceased to be used. They also noted that the pioneering plants of such re-vegetated tracks are invasive weed species and not the endemic species that are socio-economically important to the indigenous pastoralists, whose only income is through livestock herding.

Dirt tracks, formed by the first vehicles diverting from a used track onto the undisturbed grass, are softened by water from rain or snow-melt and worsened rapidly by the passage of succeeding vehicles. Washboards, ruts, potholes and corrugations formed in the softened dirt roads soon render them unsuitable for stable driving. This roughness combined with the accessibility of the surrounding terrain and the general lack of obstructive vegetation in rangelands makes it more attractive for subsequent vehicles to create their own new tracks adjacent to existing ones. The resulting dirt track network, which criss-crosses the country, does not

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consist of a single track but mostly of numerous bunched quasi-parallel tracks and has led to the deterioration and denudation of vast swathes of landscape across the entire, otherwise pristine, Mongolian steppes (see Fig. 1). The absence of fences or land tenure customs and laws, as well as snow covering on the ground, which hides the tracks for more than half the year, only serve to exacerbate the situation.

The resulting swath widths are usually in the range of 30–125 m but quite commonly reach magnitudes of approximately 900 m width, the equivalent of a 250-lane highway with contiguous lanes of 3.6 m width. The maximum width is even 6200 m (Keshkamat et al., 2011). Such widths persist for tens of kilometres across the countryside as corridors of degraded land. Batjargal et al. (2006) estimated that over 0.7 million hectares of Mongolian land is lost due to the redundant wasteful use of land for transportation.

Although Keshkamat et al. (2011) and Batjargal et al. (2006) have highlighted the environmental degradation caused by such land use, a systemic understanding of the rationality behind the creation of such wide dirt corridors has been lacking to date and is necessary for assessing the damage and countering it. In what is the first attempt to do so, this article fills the gap by investigating the corridor characteristics to identify the key geographical factors (both local and 'global') that affect the corridor widths and the extent to which they do. We consider both natural geographical factors, related to landforms and ecosystems, and artificial geographical factors, related to human settlements and engineered constructs such as roads. We postulate that the widening of the dirt roads in rangelands is clearly due to the drivers' response to the local geographical conditions, with some conditions that support widening and others that constrain it. Most of these factors act in combination, rather than singularly, and generally, this behaviour is locally varying. We apply spatial statistical techniques to investigate and compare whether the observed corridor widths are correlated with the selected geographical factors, and if so, what are the characteristics of their effect. In transport studies, such locally varying relationships have been studied by Du and Mulley (2006), Mulley and Tanner (2009), Propastin et al. (2008) and others using geographically weighted regression (GWR) (Fotheringham et al., 2002), showing promising results, which we perform in this paper as well.

As such, the major innovation in this paper is that we explain the width of dirt track corridors in Mongolia using variables from natural and social sciences. By integrating over this spectrum, we are able to formulate recommendations to mitigate the adverse effects of transportation on rangelands. Although this article restricts itself to dirt track propagation in Mongolia, this problem is by no means restricted only to this country. Rather, it appears to be a widespread phenomenon in several arid and semi-arid regions. Similar phenomena can be observed in Kazakhstan, Uzbekistan, Kuwait, Bolivia and Namibia, for example, see Allen et al. (2011), Battisti et al. (2012), Cosens (2011), Wan and Dozier (1996), Xiao et al. (2006) and Zellmer (2009).

In the following sections, the study area and methods of data collection and preparation are described, followed by a description of the geostatistical analysis, its results and implications.

2. Study area

Mongolia is a landlocked country in Northeast Asia bounded to the north by Russia and to the south by China (Fig. 2). The climate is an extreme continental climate with long, cold winters and short summers, during which most precipitation (average 20–35 cm per year) occurs. Frequent blizzards with snow-covered ground occur in the winter months, whereas thunderstorms and winds that can bring soil erosion from floods and dust storms occur in the spring and summer. From north to south, Mongolia can be broadly divided into four natural zones: Taiga forests, steppes, semi-desert and desert, although a few wetlands, alpine meadows and tundra zones are interspersed. This country hosts some of the world's most endangered flora and fauna species.

It is the world's fourth least densely populated country with a total population density of 1.7 person/km^2 (National Statistical Office of Mongolia, 2008). However, the capital city Ulaanbaatar itself contains 1.2 million of its 2.9 million people and a further 0.8 million live in the other three major cities (National Statistical Office of Mongolia, 2008). This distribution leaves the countryside extremely sparsely populated, which has contributed to the lack of nationwide formal transport infrastructure in the country – a total of only approximately 2600 km of asphalt roads for 1,564,115 km^2 of land area and rail transport is almost only along a single line from Russia to China through Ulaanbaatar, while air transport is too expensive for general use. Public transport mostly takes the form of 10-seater vans called *Furgons*. The sparse population, in

Fig. 1. The phenomenon of dirt tracks as seen at location.

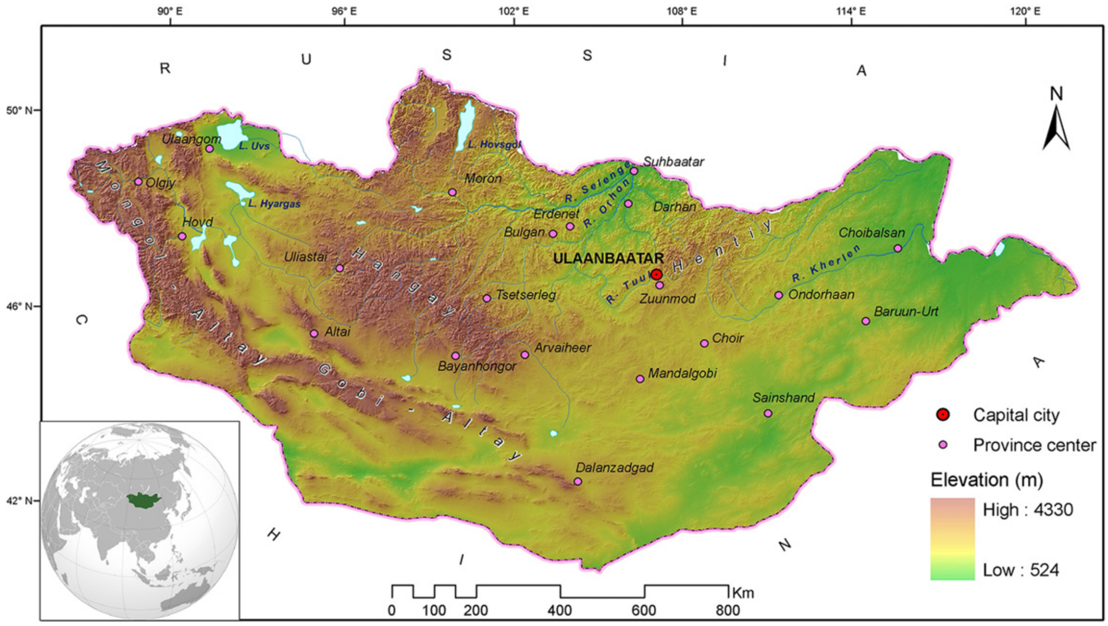

Fig. 2. Physical and political map of Mongolia.

combination with the dearth of proper road infrastructure and paucity of public transport, has recently led to a proliferation of privately owned 4-wheel drive cars throughout the countryside. However, because investment in the construction of asphalt roads has not undergone a corresponding increase due to other national priorities, the increased vehicular traffic widens the dirt tracks into dirt roads and then into dirt road corridors.

Since 2005, the Mongolian government through the Asian Development Bank and the World Bank has begun building a formal system of paved roads across the country as a means of social and economic connectivity for its people. The paving of essential arterial roads is undoubtedly the ideal solution; however, roads of this magnitude and expanse cannot be built nor funded overnight, and thus, without prejudice to future efforts in this direction, low-investment, low-risk mitigation measures to understand and reduce or control corridor widths are currently necessary.

3. Materials and methods

To assess the area damaged by the dirt roads and corridors and to investigate selected geographical factors that affect the width of the corridors, our analysis involved three stages:

1. Identification of dirt tracks and dirt track corridors in Mongolia based on satellite imagery;
2. Identification and mapping of the key geographical factors that affect corridor widths;
3. Statistical analysis of the geographical factors that affect the corridor width.

Fig. 3 presents an overview of the process, which will be described in the following subsections.

3.1. Identification of dirt tracks and dirt track corridors

The denudation caused by dirt tracks occurs on a very wide scale, usually beyond the visual range of an observer on level ground, and is noticed only from high ground or when the terrain slopes acutely, thus making its field measurement very difficult. Satellite imagery offers the best possible approach to identify the extent and spread of the dirt corridors at a country scale. Identification of dirt corridors, however, poses a challenge – at high magnification (low extent), it is impossible to identify the logic of the behaviour of each 'strand' of track, thereby making the decision, on whether to 'bundle' it into a certain corridor or not, difficult. On the other hand, at large extent (low magnification), it is not possible to identify the finer tracks clearly, and some may be missed (Keshkamat et al., 2012).

The possibility of automatic delineation of dirt road swaths using remotely sensed imageries from Landsat and Quickbird through feature extraction software such as eCognition and Imagine Objective was tested. However, this approach was not continued for further research because of two reasons. First, dirt roads could not be separated accurately in some areas due to a combination of spectral, orthographic, topographical and geometrical variability and false positives such as lineaments and dry gulches. Second, such a national scale study would require a large number of mid- and high- spatial resolution imageries, which are not freely available. However, Google Earth provides open access mid- and high-resolution imagery. Hence, we digitised corridors from Google Earth through visual interpretation and cognitive analysis.

Trained image interpreters at the Institute of Geography (Mongolian Academy of Sciences, Ulaanbaatar) visually interpreted satellite imagery, grouping quasi-parallel tracks into corridors and digitised these corridors manually on screen in Google Earth. Manual feature extraction combined with local knowledge, although more subjective than algorithm-driven machine analysis, generally leads to better results, particularly for informal features such as dirt roads (de Leeuw et al., 2011; Zhou et al., 2006). The Google Earth image database for Mongolia currently consists of a mosaic of Geo-Eye imagery (sub-metre resolution), SPOT imagery (2.5-m resolution) and Landsat imagery (15-m resolution), acquired between 2005 and 2011. Paved roads and dirt tracks could be well discerned and delineated in all the imagery due to their characteristic linearity and contrast with surrounding areas.

We identified 37 main national corridors, having a total length of 11,000 km, which is approximately 25% of all dirt roads in the

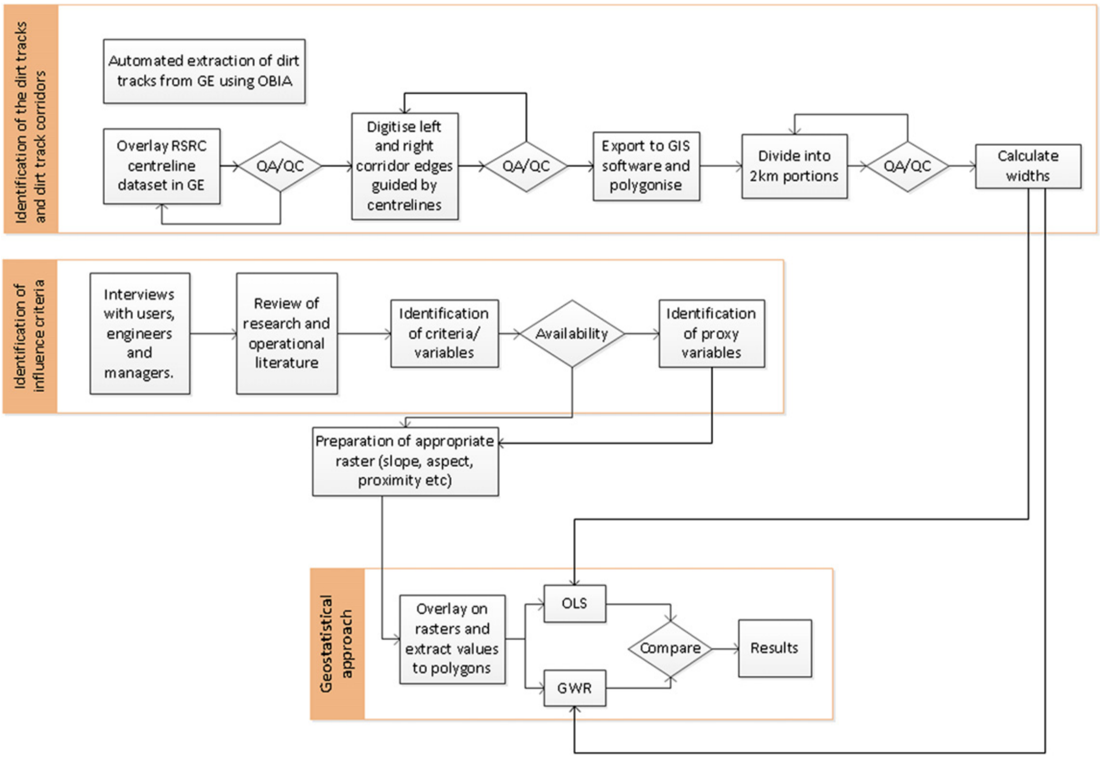

Fig. 3. Methodology followed in this study.

country (see Fig. 4) using the digital data layers of the road map of the Road Supervision and Research Centre (RSRC, 2008), which is the principal highway implementation agency of Mongolia.

The left and right margins of all the arterial road corridors were digitised on Google Earth using the RSRC (2008) spatial roads data as our primary reference data. The use of Google Earth provided us with the valuable ability to zoom (magnify) in and out of the imagery continuously, thus allowing us to capture fine detail without losing sight of the larger perspective. Both edges of a corridor were traced fully in Google Earth, one at a time for each route, and converted into a vector shape file. Fig. 5 presents an example of the digitising process of one such route corridor. The left and right border lines of each corridor were then used to create polygons in GIS software.

After deriving the route polygons, station lines were generated at every 2 km distance, and each route polygon was then split every

Fig. 4. Arterial routes of Mongolia studied in this analysis overlaid on the land-use map. (Source: Authors' elaboration based on roads dataset from RSRC, 2008).

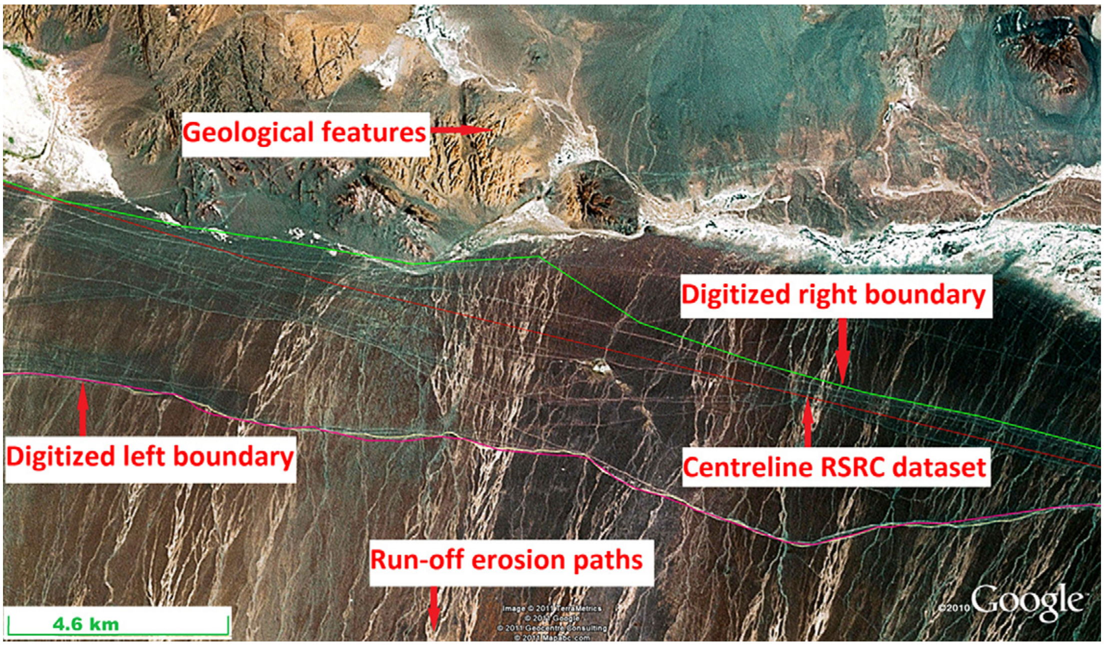

Fig. 5. Example of the digitizing process of a route corridor (Authors' elaboration on Google Earth image (Google, 2011b)).

2 km along the length, thus creating a dataset with track width attributes of each 2-km long section of each route. The average width of each portion was accordingly calculated and used for further analysis. A preliminary examination of the digitised polygons plotted on a graph (Fig. 6) indicated that less than 12% of the 11,000 km studied was under 25 m width, and approximately 65% was more than 75 m wide.

3.2. Identification and mapping of the key geographical factors

In consultation with a focus group of long-distance professional drivers, national government road engineers and private sector highway engineering consultants in Mongolia, we identified the following geographical factors (considering both natural geographical and artificial geographical features) as having potential causal relationships with the observed corridor widths:

1) Proximity to key attractors such as main towns and population centres;
2) Proximity to water features such as rivers and river crossings, lakes and marshes;
3) Terrain conditions, particularly slope and snow depth;
4) Vegetation density and greenness; and
5) Road condition, particularly washboarding.

Taberlet et al. (2007), Bitbol et al. (2009) and Shoop et al. (2006) observed that the main parameters influencing the washboarding of dirt road surfaces are the surface soil grain size, soil moisture, soil surface temperature and traffic density. Mays and Faybishenko (2000) and Taberlet et al. (2007) also observed that light and medium vehicles (such as passenger cars and SUVs), because of their 'softer' suspension systems and higher speeds, are mainly responsible for washboarding, while heavy vehicles are mainly responsible for deeper damage such as rutting. Soil temperature, moisture, and soil grain size also affect dust formation, which, when drivers attempt to evade, affects their driving trajectories.

We also observed from the National Atlas of Mongolia (Dorjgotov, 2009), as well as from Mongolian road engineers, that most of the snow in this country originates from the northwest, which is the main snow carrying wind direction, causing the deepest snow drifts on the northern aspect of the mountains. Field investigations revealed that due to an inherent local respect for productive pasture land, areas with denser (and greener) vegetation are observed as being less prone to widening than drier and less vegetated areas, which are easier to perceive as 'wasteland'. Forests and shrub-lands are uncomfortable to drive through and, hence, also avoided. Based on these inquiries and assessments, we identified 15 variables to represent the five selected geographical factors as being the most relevant to our analysis. The different variables were accordingly spatialised in a GIS environment for further spatial analysis. To maintain a common pixel size for further processing, all the raster layers representing the identified variables were either generated or resampled to a common resolution of 600 m.

Table 1 presents the factors, variables, and data sources and indicates the spatialisation process that we followed. Euclidean distance raster layers were generated from vector maps of the province centres, county centres and bodies of water. Slope and aspect maps were derived from the hole-filled Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM) of Jarvis et al. (2008). We spatialised the RSRC's Annual Average Daily Traffic (AADT) enumeration charts (RSRC, 2008) by allocating vehicle counts from the charts to the road vector map. 8-day MODIS imagery[1] for 1st–8th July 2009 for all of Mongolia was used to generate maps of topsoil Grain Size Index (GSI) as per Xiao et al. (2006), Land Surface Temperature (LST) as per Wan and Dozier (1996), Soil Moisture Index (SMI) as per Sandholt et al. (2002) and Modified Soil Adjusted Vegetation Index (MSAVI) as per Qi et al. (1994). We selected this particular period because, being the end of spring and onset of summer, it is the most optimal (balanced) period to derive variables such as MSAVI, SMI and GSI.

In total, 5248 observations (2-km section polygons) were used to fit the model in our study. The raster layers prepared in the

[1] Data obtained from the Land Processes Distributed Active Archive Center (LP DAAC) (lpdaac.usgs.gov, Accessed: May 2011).

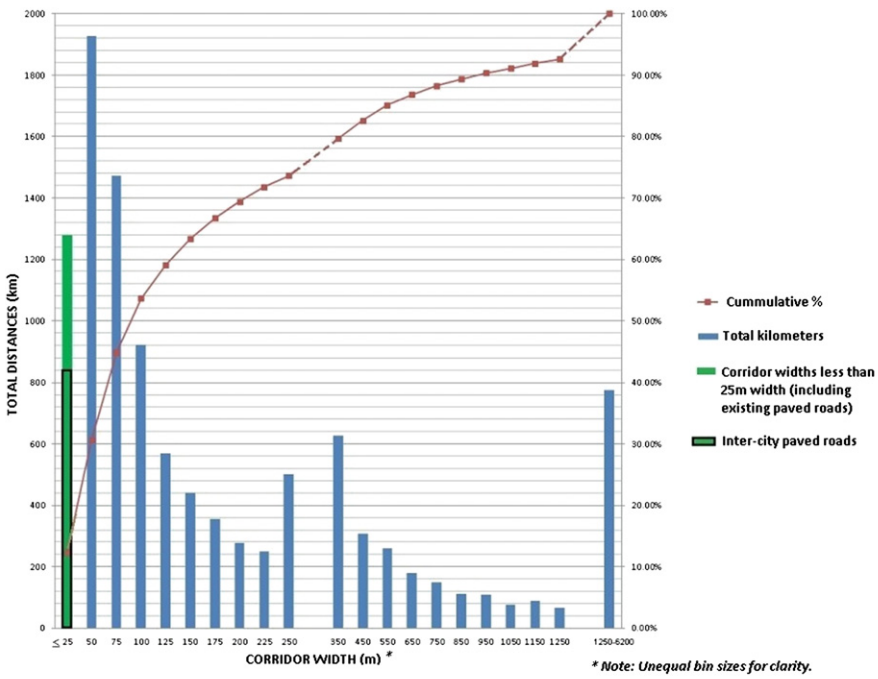

Fig. 6. Average corridor widths in meters.

previous stage were overlaid by the (split) corridor polygon layer and the polygon-raster intersection tool in the Geospatial Modelling Environment (Beyer, 2009) was used to calculate the mean value of the raster cells of each variable for each section polygon.

3.3. Statistical analysis of the geographical factors that affect corridor width

To ascertain the significance and magnitude of the geographical factors' effect on the corridor width, an inferential statistical analysis was conducted by comparing the observed parameter corridor width (as the dependent variable) with local values of the identified criteria layers (as the independent variables) using geographically weighted regression (GWR). GWR can effectively handle the spatial autocorrelation and non-stationarity inherent to spatial data, unlike conventional regression techniques, such as ordinary least squares (OLS), which can only produce average and global parameter estimates. GWR can produce local parameter estimates that can be used to ultimately generate mathematical equations, which can be used elsewhere to identify zones that may be susceptible to widening (Gao and Li, 2011; Li et al., 2010; Propastin et al., 2008). To confirm if the local parameters indeed have a strong effect on the dirt track propagation, both OLS and GWR were applied and compared in this study.

3.3.1. Ordinary least squares regression

Multi-collinearity of the independent variables can be tested using a threshold for the Variation Inflation Factor (VIF), as interrelated variables can mislead the result considerably. Stepwise OLS can then be employed to explain the average width of the dirt roads based on the geographical variables using a non-spatial statistical package for the entire dataset at once and for each of the 37 corridors separately. The regression can be presented in the form of Eq. (1):

$$y_i = \beta_0 + \sum_k \beta_k x_{ik} + e_i \quad (1)$$

where y_i is the predicted value of the response variable at location i, β_0 is the intercept, β_k is the slope coefficient for the independent

Table 1
Preparation of variable layers.

Factor	Variable	Source	Preparation
Proximity to population centres	Distance to province centre Distance to county centre	NGIC (Mongolian National Geo-Information Centre for Natural Resource Management, www.mne-ngic.mn)	Vector data->Euclidean Distance map
Proximity to water features	Distance to main rivers Distance to secondary rivers Distance to main river crossings Distance to secondary river crossings Distance to lakes and marshes		
Terrain condition	South aspect (snow depth) Terrain slope	SRTM-DEM	Classified processed DEM raster
Road condition	Total Traffic density Ratio of light-to-heavy traffic	RSRC	Table->vector ->raster
	Soil grain size (GSI) Land surface temperature (LST) Soil moisture index (SMI)	MODIS – 8-day image	Raster calculation and resampling
Vegetation	Vegetation index (MSAVI)		

geographical variable k, x_{ik} is the value of the variable k at location i, and e_i indicates the prediction error for location i. In this equation, the estimates of the model parameters are assumed to be spatially stationary.

To verify the spatial stationarity of the OLS model, Moran's I was calculated for the residuals of the model prediction using GIS software (ArcGIS). The OLS model was then calibrated to manage the spatial dependence using a spatial autoregressive model in Spatial Analysis in Macro-ecology (SAM) software (Rangel et al., 2010).

3.3.2. Geographically weighted regression

Geographical Weighted Regression (GWR) has been conducted in SAM (Rangel et al., 2010) to manage the issue of spatial autocorrelation and to investigate the spatial variability in the effect of the selected geographical variables. This process can help the examination of the spatial pattern of the local estimates to obtain better understanding of possible hidden causes of the observed values (Fotheringham et al., 2002). The GWR model extends OLS global regression by creating a local regression equation for each observation point and can be expressed by Eq. (2) (Fotheringham et al., 2002):

$$y_i = \beta_{0(\mu i,i)} + \sum_k \beta_{k(\mu i,i)} x_{ik} + e_i \quad (2)$$

where $(\mu i,i)$ is the spatial location of observation point i, $\beta_{0(\mu i,i)}$ is the intercept for location i and $\beta_{k(\mu i,i)}$ represents the local slope coefficient for independent variable k at location i.

Parameter estimates in GWR can be calculated by giving a weight to all observation points around a specific point i based on their spatial proximity to it. The observations closer to point i have greater effect on the local parameter estimates for the location and, thus, are weighted more than points further away (Fotheringham et al., 2002). As we study dirt track corridors (widening from a mostly straight centre line), the observations in our study are distributed linearly, rather than in circular buffers.

The estimated parameters in GWR are highly dependent on the bandwidth size of a selected kernel. As the bandwidth increases, the parameter estimates will be closer to that of the OLS global model. Conversely, as the bandwidth decreases, the parameter estimates will highly depend on the observations near the regression point i, and increased variation will occur. Therefore, selecting the optimum bandwidth is very important in GWR. The optimum bandwidth is calculated either using a cross-validation technique (CV) or using the corrected Akaike's Information Criterion (AICc). Bandwidth selection based on the AICc is used in this study, as the lower the AICc, the better the model prediction. Once the bandwidth calibration process is complete, GWR uses the optimal bandwidth to fit a weighted regression model at each point, with the parameter estimates being the output. Through multiple iterations, the optimal bandwidth was identified to be 100.11 km. That is, observation points from an extent of about 100 km around its location were included in local regression for observation i.

The t-value for each parameter estimate and each regression point was accordingly been used to test if the effect of a certain geographical variable is significant at the 90% confidence level for specific observation points. Significant effects were then spatially mapped for each variable.

4. Results

This section presents the results of our OLS and GWR analyses. We will demonstrate that the selected geomorphological and human-induced factors can explain the creation of dirt tracks well, provided we allow the variables to vary across the landscape in a GWR. First, we discuss the results of the OLS analysis to conclude that the variables are locally varying, justifying the use of GWR, which is discussed next.

4.1. Ordinary least squares regression

Stepwise linear regression for all segments together (the global model) resulted in a R^2 of 0.05, meaning that only 5% of the average widths of dirt road corridors can be explained by some of the geographical variables. Proximity to main rivers and their crossings, proximity to province centres, lakes and slopes, aspect, light-to-heavy traffic ratio, MSAVI, GSI and soil moisture variables were observed to be significant in the global OLS model. Slope, vegetation, distance to lake, main river and its crossings and soil moisture acted as constraints to the widening of dirt roads, whereas the others appeared to aid it.

Stepwise regression was also applied individually for each of the 37 corridors. The coefficient of determination improved significantly, in the range of 0.13–0.7, compared with all corridors combined. From the results, it was clear that some variables were playing an important role in some corridors but not for all of them. The descriptive statistics for the corridor-wise OLS are provided in the Supplementary online materials.

Calculation of the local Moran's I for the residuals from the global OLS model indicated that the effect of spatial autocorrelation is highly significant in a few specific corridors, particularly those showing high R^2 in OLS, thus rendering their 'good' results questionable. Moran's I for the residuals of all corridors in the dataset was 0.7, indicating a high spatial autocorrelation. Given the z-score of 58.84, these results also indicated there is less than a 1% likelihood that this clustered pattern could be the result of random chance. Thus, it is not likely that the corridor width can be explained well by other (geographical) variables when global OLS regression is used because the spatial dependence (autocorrelation) of the residuals violates the basic assumption of the OLS regression. Correcting for spatial autocorrelation in the global model improves the R^2 to a modest 11% compared with the model that did not consider the spatial effect. We consider this score insufficient to draw further conclusions on dirt track propagation. Given the high local variability that was observed, a GWR analysis was necessary.

4.2. Geographically weighted regression

Using a Gaussian spatial function, the optimised Fixed Bandwidth (b) at 100.11 km, and the 15 predictor variables, the GWR analysis yielded an adjusted R^2 of 0.45, meaning that GWR could explain 45% of the corridor widths using our set of geographical variables – a very good score considering that this is incorporating human behaviour. The model summary of the GWR results and comparison with the OLS results are presented in Table 2.

Table 2
Model summary showing of GWR and OLS results.

Comparison measure	GWR	OLS
Sigma	235,636	633
Effective number of parameters	242	16
Akaike Information Criterion (AICc)	80,072	82,615
Correlation coefficient (r)	0.689	0.231
Coefficient of determination (R^2)	0.475	0.054
Adjusted r-square (R^2 Adj)	0.449	0.051
F (R^2)	18.738	19.743
P-value (R^2)	0	<.001

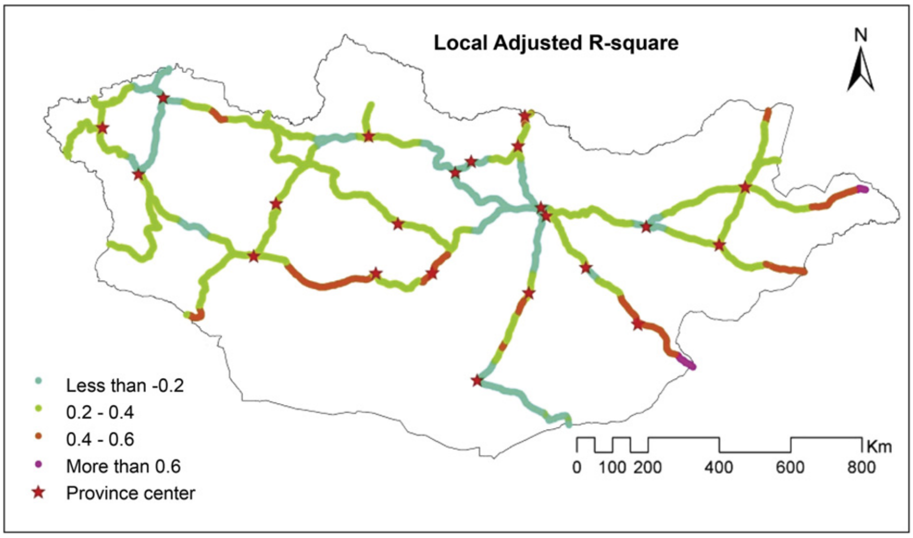

Fig. 7. Correlation results of GWR analysis.

The local correlation results (i.e., local adjusted R^2) obtained by the GWR analysis were mapped to observe the model fit spatially, as shown in Fig. 7. A few areas in the central, southern, and western parts have a weak model fit (<0.2), while most of the areas have moderate model fits (>0.2).

The model validity can be verified by examining the residuals. Fig. 8 compares the residuals of GWR and OLS. It can be observed that, as expected, the GWR model fits the data better; i.e., there is less spatial autocorrelation error in the GWR analysis. Moran's I for the GWR residuals was 0.23, while for the OLS residuals, it was 0.39 (for the same bandwidth), implying that GWR addresses the issue of spatial autocorrelation well.

To understand the effect of each of the local geographical factors on the dirt track corridor width, the GWR coefficient of each parameter qualified by its *t*-value (at least 90% confidence level) was mapped to the polygon shape file and is described below for each of the five factor sets.

4.2.1. *Proximity to population centres*

The variable proximity to province centre (Fig. 9(A)) has the strongest effect in the national capital region – as the distance to the province centre increases, the corridor widths increase. This result could occur because most of the province centres typically have a 10–20 km asphalt approach road. However, near the province centres of Arvayheer and Uliastay, this effect is reversed due to mountainous terrain. However, proximity to county centres (Fig. 9(B)) has a negative effect (the corridors are wider near the county centres), as drivers branch off from the main trajectory and head straight for their final destination (and vice-versa), except for the Sainshand-Zamiin Uud route, where proximity to streams appears to overpower the general trend.

4.2.2. *Terrain conditions*

Our expectation that the greater the slope, the narrower the corridor was confirmed (Fig. 9(C)). In the areas near Ulaanbaatar and Baruun Urt, the effect is more significant. The effect of aspect (Fig. 9(D)) is understandably only present in very small areas, in the Hentiy mountain range (near Ulaanbaatar, Bagannuur and Choir), the more southern the road, the greater the width, whereas in other areas, the more northern the road, the wider the corridor. This result could occur because in those areas, there is less snow coverage in the northern aspect due to local meteorological conditions.

4.2.3. *Proximity to water features*

Fig. 9(E)–(I) demonstrate that in general, the proximity to main rivers and seasonal streams has a positive correlation with the width (the corridor is narrower when it is closer to main rivers and streams), except for smaller rivers and lakes/marshes, where there

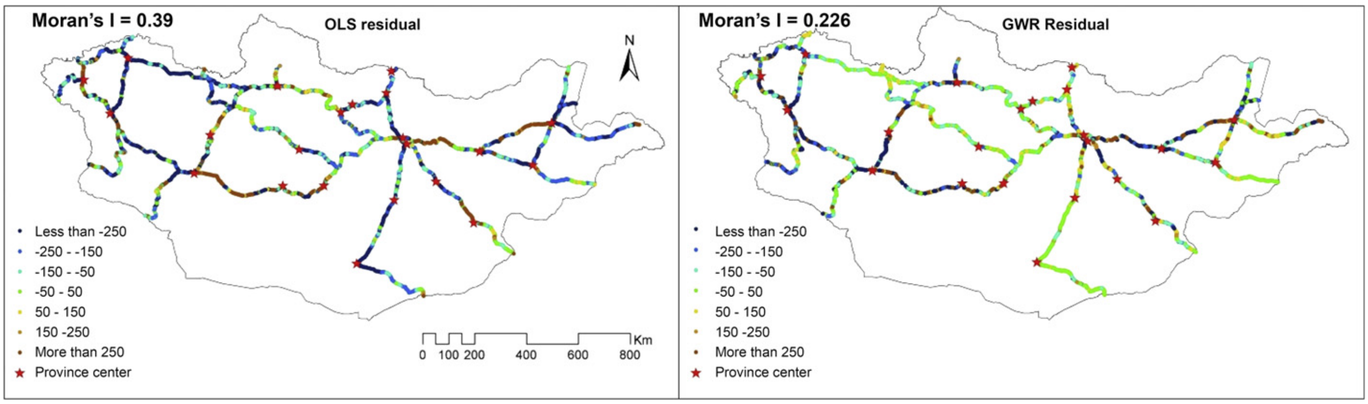

Fig. 8. Comparing the residuals of OLS and GWR.

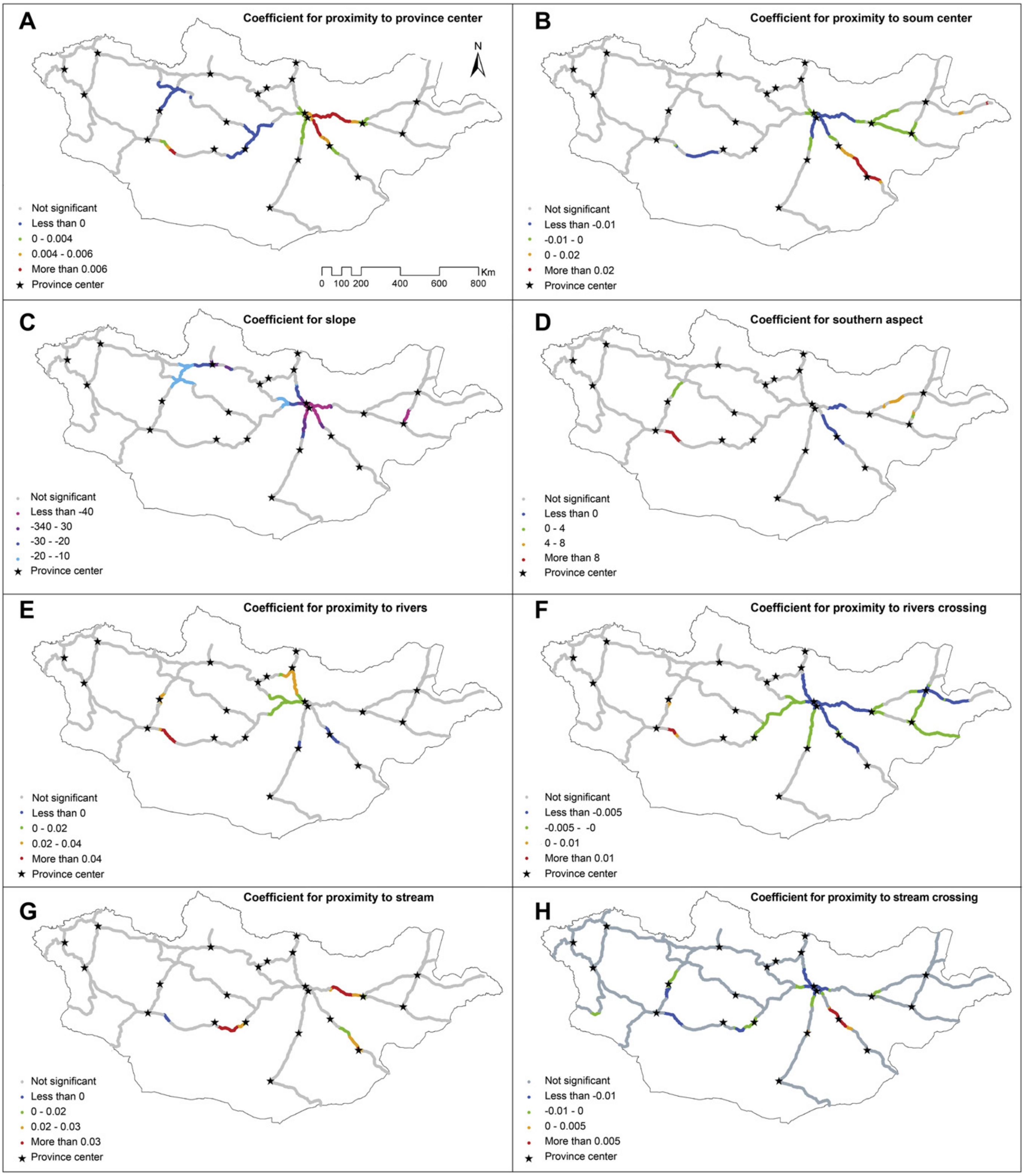

Fig. 9. Influence of local geographical factors on the dirt track corridor width.

is a reverse effect (the closer the corridor is to a small river or marsh, the wider it is), perhaps because of the muddiness associated with such features. Conversely, the proximity to river crossings and seasonal stream crossings had a negative effect on the width (the corridor gets wider as it gets closer to river and stream crossings).

4.2.4. Road condition

Fig. 9(J)–(M) illustrate that the higher the traffic density, the greater the width, except where paved roads are already present. The greater the proportion of light vehicles in traffic, the larger the width, except when in combination with close proximity to a stream, where this effect is reversed, e.g., in Bayanhongor and Arvayheer.

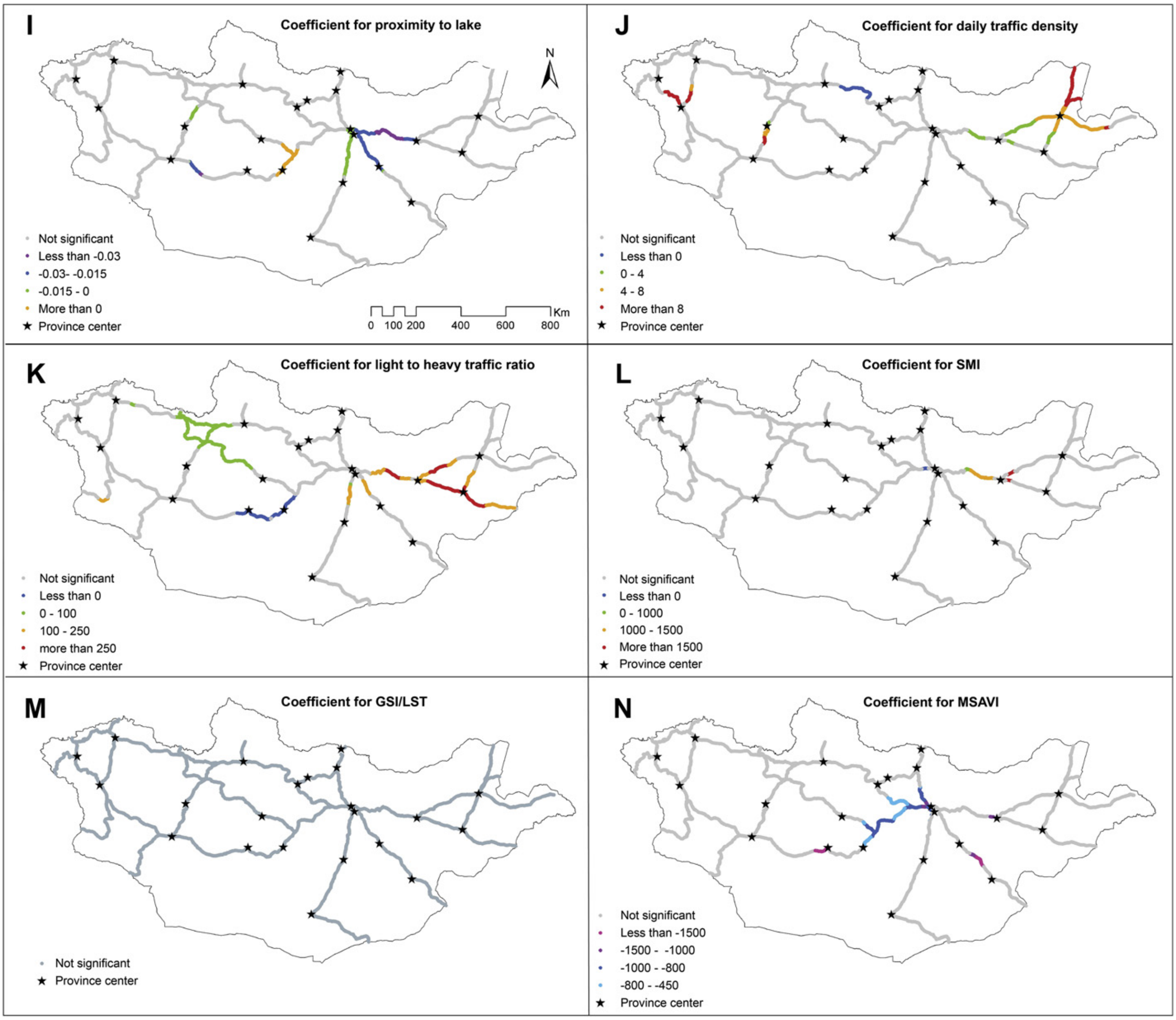

Fig. 9. (*continued*).

The effect of SMI was significant in a very small area, and it was positive (the wetter the soil, the wider the corridor). The GWR results indicated that GSI and LST were not locally significant, even though the OLS indicated that it was significant. This result suggests that GSI and LST are global variables.

4.2.5. Vegetation

As anticipated, the MSAVI effect (Fig. 9(N)) was that the 'greener' areas had narrower corridors. Although scientifically, we know that the low-height sparse vegetation implies 'vulnerable land', the drivers appear to perceive it as 'wasteland'.

5. Discussion

The analysis indicates that the corridor widths are generally not random but are a consequence of human (driver) response to the selected geographical factors. Neither the effect of such a factor, nor its magnitude, is constant throughout the country but varies over space. Not just to a lesser or greater effect, it may even have the reverse effect locally. It is the combination of circumstances (i.e., the geographical factors) that causes drivers to make a routing decision at a particular point in space and time, rather than a single parameter itself. Because of this local-centricity, it is possible that some other locally significant parameters may be missed. Local inhabitants cite examples of how small discoveries of mineral deposits led artisanal miners to rapidly extract and truck the ore away, creating, in the process, large dirt track corridors that still scar the pasture lands several years after the mine was exhausted. It is also possible that a few tracks are purely 'desire paths'. These are exceptions that our model cannot cover; however, our model does address the general trend.

Referring back to the results section and Fig. 2 for specific locations, in the region east of Ondorhaan, the proximity to county centre, proximity to river crossing, daily traffic density, light-to-heavy traffic ratio, and southern aspect affected the dirt road propagation. In the central regions, south and east of Ulaanbaatar, most of the considered environmental variables except MSAVI, GSI, and LST were significant. However, in the west and north of

Ulaanbaatar, the proximity to main rivers, river crossings, seasonal stream crossings, terrain slope, and MSAVI were significant. This result could arise because this region consists of the main river basins of the Orhon, Selenge and Tuul rivers and has a dense network of perennial water channels compared with the remainder of the country. In the northern part of Hangay region and Hovsgol region, proximity to province centre, proximity to lakes and marshes, traffic density, light-to-heavy traffic ratio, and slope had an effect on dirt road propagation, whereas in the southern part of Hangay region, proximity to province and county centres, proximity to main rivers and their crossings, and lakes, light-to-heavy traffic ratio, and MSAVI were significant. In Western Mongolia, traffic density, light-to-heavy traffic ratio, and proximity to stream crossing significantly affect the dirt road propagation.

5.1. Utility of this study

Given that a typical road development process takes between 10–15 years, especially over such large distances, we believe the results of this study can serve to urgently address the problem, increase social awareness and initiate mitigation measures. Senior highway managers and engineers in Mongolia are fully aware of the problem of environmental degradation due to dirt track propagation but expressed helplessness at the situation. The completion of an asphalt road is believed to be the only possible solution.

We, however, believe that by identifying and isolating the geographical factors that influence such driving behaviour, we can help to initiate immediate mitigation measures in the hotspot zones by implementing appropriately-located corrective measures and aids. For example, in the majority of the country, there is a severe lack of bridges for crossing rivers; thus, drivers seek out shallow stretches of river where they may cross. To reach this point, they first fan out, and then when they see the river, narrow in again. If such behaviour were understood, appropriate traffic information signboards/marker stones could be placed just before the fanning-out zone to induce drivers to stay on one track. Another example of such mitigation measures would be the identification of areas that exhibit characteristic signatures of waterlogged roads. In such stretches, the soil could be stabilised by 5–10% cement mixed in the soil and graded, thus enabling smoother travel and reduced degradation. Moreover, our analysis demonstrated that near county centres, there is a sudden and drastic widening of corridors (Fig. 9(A) and (B)). This phenomenon is due to drivers fanning-out from the main trajectory as they branch out to go to their desired side of town (or start from a place in town and fan out searching for the main route). A designated improved ring-road around the town, as illustrated in Fig. 10, could serve the people within the town and help to reduce the damage caused by this practice.

Other similar cost-effective remedies can be envisaged by local planners and engineers if the locations where they are needed can be identified rapidly and easily.

5.2. Sources of error

This analysis had to manage the temporal variability typically associated with a study at a large spatiotemporal scale. The locations of topographic features such as main rivers, secondary rivers and lakes vary spatially, seasonally and decadally. Main rivers meander, secondary rivers abandon old courses and select new ones, and lakes and marshes can shrink in volume, thereby altering shorelines. Concurrently, there is seasonal variability in vegetation quality, soil moisture, snow cover on the ground, etc.; thus, there is a temporal effect on the corridor widths. We considered an analysis of the temporal variability of the tracks to be beyond the scope of this study.

Moreover, only the damage due to vehicular movements was considered in this analysis. The actions of other social, geographical and environmental agents, such as erosion due to wind, water run-off, snow-melt, percolation, permafrost melt, livestock grazing movements, (see for example De Jong and Epema, 2002) etc., were not considered in this analysis. The consideration of these factors would require more extensive and complex modelling and was not performed.

The subjectivity in cognitive digitising of the corridors also affects the accuracy of the digitised route polygons. Although a multi-tier quality control mechanism was established to ensure constancy of intent and procedure to reduce this error, the possibility of the introduction of errors still exists.

Perhaps the weakest link of our method is our use of Google Earth itself – a mosaic of images of various indeterminate and unspecifiable resolution, seasonality and accuracy. Although Google does not provide an estimate of Google Earth's accuracy, Potere (2008) proved that the overall horizontal accuracy for most developing countries is approximately 44.4 m. These orders of accuracy for input data are acceptable given the extent of the study. Site verification using GPS at several locations was performed and

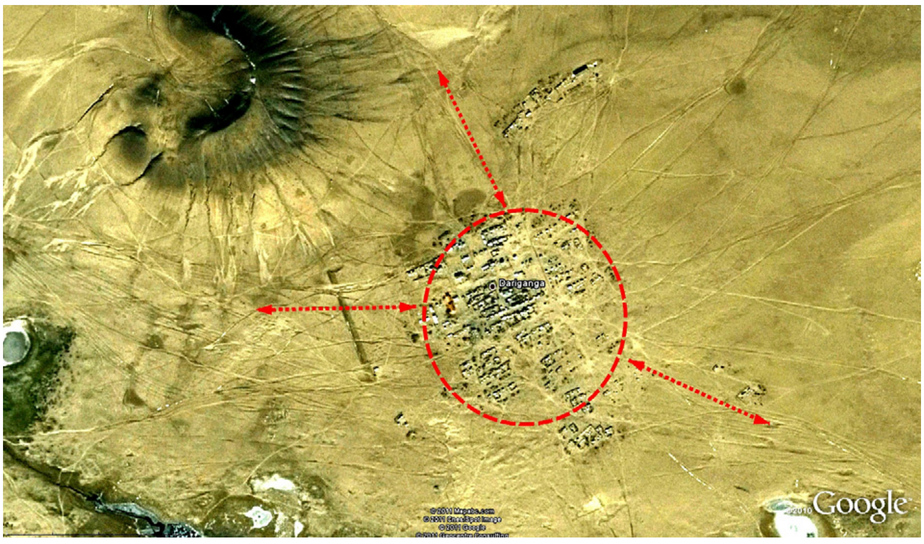

Fig. 10. A ring-road around a county centre can reduce the land degradation considerably. (Source: Authors' elaboration on Google Earth image (Google, 2011a)).

considered acceptable. Like other drivers who drive along these corridors, we too, when on site, could not see the full extent of the corridor width. Google Earth was therefore, without a doubt, despite its limitations, the best possible resource available for this study.

6. Conclusions and recommendations

The main conclusion that can be drawn from this study is that local geographical factors, such as proximity to towns or rivers, terrain conditions and washboarding, can explain corridor widening due to vehicular driving. These factors exhibit strong spatial non-stationarity, which was confirmed using GWR. The GWR model demonstrated a significant improvement over the global OLS model and provides a better fit for the 11,000 km of digitised dirt track corridor data. This improvement was also confirmed by the increase in the adjusted R^2 values for the entire study area.

Given that the issue of corridor widening can now be rationalised, it is entirely possible to locate, identify and install appropriate mitigation measures or counter-measures to reduce the land degradation that is occurring unabated.

In addition to mitigation measures, we recommend the use of these findings in the design of the actual alignment of asphalt roads when planned, thus following a user-centric approach. Otherwise, for many users, the 'pull' of the studied variables will be greater than the temptation to drive on a paved road, which was aligned as per a high-level technical vision. We further recommend that more institutional efforts should be made to regularly assess and monitor dirt track propagation. The creation, shifting and modification of these tracks could then be verified against the seasonal behaviour of the rivers, streams, nomadic practices, and ground cover and be used to adjust mitigation measures.

Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2012.10.043.

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