GIS Approaches to Understanding Connections and Movement through Space

Gemma Davies

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Abstract

The overarching theme of this work is an exploration of ways in which GIS can be used to analyse connections or movement through space in a wide variety of contexts. The published work focuses upon the application of both network and raster-based techniques at a variety of scales.

A review is provided summarising the breadth of applications that currently use GIS to model connectivity or movement through space. This is followed by a series of published work in this field. This includes both raster and network approaches to assessing journey-time exposure to air pollution; exploring the impact of artificial lighting on gap crossing thresholds of bats; examining the presence of food deserts in rainforest cities; assessing urban accessibility and its influence on social vulnerability to climate shocks; and understanding of the impact of segregation on everyday patterns of mobility.

With a diverse range of application areas and variety of spatial scales ranging from 2 - 605,000km^2, this published work highlights the ways in which GIS can be implemented in new ways to improve understanding of connections and/or movement through space.

Contents

Publications submitted

1. **DAVIES, G.** & WHYATT, D. 2009. A least-cost approach to personal exposure reduction. *Transactions in GIS,* 13, 229-246.

2. **DAVIES, G**. & WHYATT, J. D. 2014. A network-based approach for estimating pedestrian journey-time exposure to air pollution. *Science of the Total Environment,* 485, 62-70.

3a. DAVIES, G., HALE, J. & SADLER, J. Modelling functional connectivity pathways for bats in urban landscapes. Proceedings of the GIS Research UK 20th Annual Conference. Lancaster University, Lancaster, 2012. 95-100.

3b. HALE, J. D., FAIRBRASS, A. J., MATTHEWS, T. J., **DAVIES, G**. & SADLER, J. P. 2015. The ecological impact of city lighting scenarios: exploring gap crossing thresholds for urban bats. *Global Change Biology,* 21, 2467-2478.

4. **DAVIES, G**., FRAUSIN, G. & PARRY, L. 2017. Are there food deserts in rainforest cities? *Annals of the American Association of Geographers,* 107**,** 794-811.

5. PARRY, L., **DAVIES, G.,** ALMEIDA, O., FRAUSIN, G., DE MORAÉS, A., RIVERO, S., FILIZOLA, N. & TORRES, P. 2018. Social vulnerability to climatic shocks is shaped by urban accessibility. *Annals of the American Association of Geographers,* 108, 125-143.

6. **DAVIES, G.,** DIXON, J., TREDOUX, C., WHYATT, J.D., HUCK, J., STURGEON, B., HOCKING, B., JARMAN, N., BRYAN, D. 2019. Networks of Dis(connection): Mobility practices, tertiary streets and sectarian divisions in north Belfast. *Annals of the American Association of Geographers.* (Published online 30/5/2019)

Acknowledgements

I am grateful to all of my co-authors for their often significant role in helping these papers come into being. This includes endless weeks of fieldwork from Gina Frausin, who managed to persuade a staggering 100% of the shop owners in our study towns within the Brazilian Amazon to take part in our survey, and Bree Hocking and Brendan Sturgeon who literally wore through shoes walking endless miles around North Belfast going door to door to recruit participants. I am also grateful to Luke Parry and John Dixon who as PIs invited me to join their project teams.

My greatest thanks go to the one person, without whom this PhD would never have come into being, that is Duncan Whyatt. It was Duncan who first got me interested in GIS as an undergraduate back in 1998. Then when I returned to work in the department in 2001 gave me opportunities to work on many of the projects he was involved with. In 2008 he supported me as I led the writing of a paper for the first time. I have lost track of how much feedback I have received from him over the years, usually in the form of his famous red pen. He was the one who encouraged me to work towards this PhD by Published Work, long before I would ever have dreamt of pursuing it. Most of all I want to thank Duncan for believing in my abilities long before anyone else (myself included), and for the endless encouragement he has provided along the way. None of this would have happened without him and I am hugely grateful for all his support in getting me this far.

Author declaration

Each of the papers included in this PhD by published work was produced with varying contributions from a number of co-authors. My contribution to each of the papers is outlined below.

DAVIES, G. & WHYATT, D. 2009. A least-cost approach to personal exposure reduction. *Transactions in GIS,* 13, 229-246.

For this paper I undertook all of the data analysis, background reading and writing, with input and guidance from Duncan Whyatt.

DAVIES, G. & WHYATT, J. D. 2014. A network-based approach for estimating pedestrian journey-time exposure to air pollution. *Science of the Total Environment,* 485, 62-70.

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I have paired these articles as a single submission, the first being a published conference paper which also demonstrates my contribution towards the subsequent paper in Global Change Biology.

I undertook all of the spatial analysis and writing for the conference paper. My contribution to the Global Change Biology paper was in designing a method to translate the empirical data and binomial model into a spatial model. James Hale and Jon Sadler designed the field surveys and also took part in analysing the data. James Hale and Jon Sadler wrote the paper with contributions from other co-authors, including myself.

The Global Change Biology paper has also been submitted by James Hale as part of his PhD by Published Work at the University of Birmingham in 2015.

DAVIES, G., FRAUSIN, G. & PARRY, L. 2017. Are there food deserts in rainforest cities? *Annals of the American Association of Geographers,* 107, 794-811.

For this paper I undertook all of the spatial analysis, background reading and writing. Gina Frausin carried out the field work for this research. Luke Parry undertook all statistical analysis and contributed to the writing.

PARRY, L., DAVIES, G., ALMEIDA, O., FRAUSIN, G., DE MORAÉS, A., RIVERO, S., FILIZOLA, N. & TORRES, P. 2018. Social vulnerability to climatic shocks is shaped by urban accessibility. *Annals of the American Association of Geographers,* 108, 125-143.

I contributed to this paper by undertaking all of the spatial analysis, developing a multi-modal river and road network, and carrying out analysis to compute the remoteness index. Luke Parry led the writing and statistical analysis with contributions from other co-authors.

DAVIES, G., DIXON, J., TREDOUX, C., WHYATT, J.D., HUCK, J., STURGEON, B., HOCKING, B., JARMAN, N., BRYAN, D. 2019. Networks of Dis(connection): Mobility practices, tertiary streets and sectarian divisions in north Belfast. *Annals of the American Association of Geographers.* (Published online 30/5/2019)

For this paper I undertook all of the spatial analysis, background reading and writing. Statistical analysis was undertaken by Colin Tredoux. Brendan Sturgeon and Bree Hocking recruited participants, and provided other guidance, Jonny Huck developed the app used to collect the GPS data and worked with me on the processing and cleaning of the GPS data. Neil Jarman and others provided guidance on community affiliation and John Dixon and Duncan Whyatt provided helpful guidance on the structure and direction of the research.

Introduction and research context

My role as GIS Officer within the Lancaster Environment Centre has provided me with a range of opportunities to apply GIS approaches within different discipline areas including: ecology, food security, air pollution, psychology and mobility; thus helping create new metrics and address questions which could not easily be answered otherwise. The focus of my work has been practical application of GIS techniques to answer real world questions. This in turn has led to publications in a wide range of topics, many of which interconnect with strong methodological or topical links. I present a subset of my publications for consideration for PhD by Published Work.

Whilst covering a broad range of topics and sub-disciplines, each of the submitted papers applies GIS in different ways to further understanding of connections and movement through geographical space. Application areas include: mobility and segregation (Davies et al., 2019); food security (Davies et al., 2017, Parry et al., 2018); habitat connectivity (Davies et al., 2012; Hale et al., 2015); and journey-time exposure to air pollution (Davies & Whyatt, 2009; Davies & Whyatt, 2014). I have submitted for consideration only those of my publications most focused on the theme of applying GIS to the understanding of connections through space. These papers, however, often interlink with other publications I have co-authored and which provide further understanding within specific subject areas. Where links exist between those papers submitted for consideration and my other published work, these are highlighted within the paper summaries.

Throughout this supporting paper I frequently refer to ‘we’ as much of this work was undertaken with significant collaboration from co-authors. My contribution to each is outlined in the author declaration.

Paper summaries and contribution to field

DAVIES, G. & WHYATT, D. 2009. A least-cost approach to personal exposure reduction. *Transactions in GIS,* 13, 229-246.

Summary

This paper was born out of a broader ESRC-funded project, which examined factors influencing children's journeys to school (Walker et al., 2011; Pooley et al., 2010a; Pooley et al., 2010b; Walker et al., 2009; Bamford et al., 2008; Whyatt et al., 2008). The aim of the paper was to explore the potential of adopting raster least-cost path techniques to identify routes that would minimise journey-time exposure to air pollution. As pollution concentrations vary continuously throughout space, a raster model was chosen in order to model movement through any traversable space, e.g. parkland. Detailed pollution surfaces representing average concentrations of CO and PM_{10} during the morning school run (8-9am) were generated using the dispersion model ADMS Urban, then used as cost surfaces in the least-cost model. A detailed analysis mask was then created to represent traversable space across the study area. This ensured realistic movements through the urban landscape, including footpaths and narrow gateways. A cost distance surface was then created. This represented the cumulative air pollution exposure of an individual as they moved away from the school. Least-cost paths were then generated to each participant's home address. Comparing the cumulative journey-time exposure over the course of both the modelled and actual routes taken (captured by participants using GPS tracking), showed that where alternative routes away from main roads were available, reductions in journey-time exposure of up to 20% were possible, leading to potentially significant health benefits.

Contribution to field

This paper was designed to provide a new method for modelling least-polluted routes to help minimise journey-time exposure to air pollution. At the date of publication, only one previous study had attempted to model least-polluted routes. This adopted a network analysis approach with limited success (Hertel et al., 2008). While raster least-cost path analysis has been widely applied in disciplines such as ecology for predicting animal movement, this is the first time such methods have been adapted to provide estimates of journey-time exposure.

The use of a detailed and high-resolution analysis mask when undertaking least-cost analysis is also novel in relation to existing literature. For movement to be accurately modelled a detailed analysis mask was created at a fine enough resolution to capture both pavement width and gaps through barriers, such as gateways. Linear barriers to movement, such as walls, were first buffered to ensure that no false gaps appeared. High resolution analysis was essential in order to accurately model potential routes. This analysis made use of detailed Ordnance Survey Master Map data, which was newly available at the time. Working at a high-resolution of $0.5m^2$ with a very detailed analysis mask overcame many of the challenges of spatial inaccuracy cited in studies elsewhere.

The method developed in this paper provides a means by which to model least-polluted routes across open space. The results generated were some of the first to be published showing the potential of choosing least-polluted routes to reduce exposure to air pollution. GPS tracks of actual journeys to and from school provided insights into route choice, demonstrating that route choice was often complex and not always the shortest route to school. This route data provided scope for more accurate assessment of the likely gains from re-routing journeys to less polluted routes, and also highlighted the fact that other priorities may influence route choice. These themes are explored further within the critical review. This was amongst one of the earliest studies to focus on air pollution and school children, an area which has since received significant attention.

Links to my other work

Prior to this paper I had developed skills in dispersion modelling during work carried out for two previous studies commissioned by Halton Borough Council (Burgess et al., 2004; Whyatt & Davies, 2007). Working on the journey to school project helped me develop a greater understanding of factors affecting the school journey, as well as generating routes that could be used as a baseline for this study (Bamford et al., 2008; Pooley et al., 2010a; Pooley et al., 2010b; Walker et al., 2009; Walker et al., 2011).

The understanding of journey-time exposure developed here, significantly informed the work I went on to publish in Davies and Whyatt (2014).

Journal standing and citations

Transactions in GIS is an international journal, specialising the application and development of GIS and spatial science. It has an impact factor of 1.91.

To date this article has 22 citations.

DAVIES, G. & WHYATT, J. D. 2014. A network-based approach for estimating pedestrian journey-time exposure to air pollution. ***Science of the Total Environment,*** **485, 62-70.**

Summary

Having identified potential for reducing journey-time exposure to air pollution in Davies & Whyatt (2009), this paper sought to test this further by exploring potential reductions between multiple origin and destination pairs and multiple variations in background pollution levels and meteorological conditions. As we were working with multiple scenarios at a city scale, this time we chose to use a network data model.

The study revealed significant variations between routes generated for different days and therefore the importance of tailoring least-polluted routes to time-specific conditions. Sometimes significant changes in exposure levels were found with only subtle changes in route (such as walking on the opposite side of the road), thus highlighting the importance of detailed network elements. Including metabolic rate within network attribute calculations also enabled the model to identify differences in exposure with changes in walking or running speed. This allowed routes to be tailored not only to specific meteorology and background pollution concentrations, but also to variations in activity level and individual physiology, for example the difference between a parent and child walking the same journey to school.

Contribution to field

Whilst other researchers have applied network analysis to model journey-time exposure, I expanded this approach in a number of ways, adding new levels of realism. Novel elements of this work include:

1) My network elements included pavements either side of main roads, rather than just centre lines. Prior to this paper all previous has adopted a road centre-line approach, perhaps with additional paths captured. To date only one other study has subsequently sought to model pavements either side of the road (Mölter & Lindley 2015). By modelling pollution levels at the location of the pavements rather than road centre lines, modelled pollution levels more accurately reflect concentrations experienced by the pedestrian. As pollution levels vary considerably on different sides of the road depending on wind speed and direction, this significantly enhanced the ability to model subtly different routes, with significant reductions sometimes found by simply walking along the opposite side of the road.
2) While other journey-time exposure studies have focused on average pollution concentrations, I modelled day-specific pollution concentrations based on local meteorological conditions and corresponding background pollution concentrations. This enabled variations between different least polluted routes to be evaluated. Significant variations in least-polluted route were found between days for the same pairs of origins and destinations, thus highlighting the importance of not simply considering average pollution concentrations, as is generally the case in other studies.
3) Thirdly, I accounted for inhaled dose. I developed a method for incorporating both physiology and activity level into estimates of journey-time exposure. All modelling studies to date have quantified exposure based on ambient concentrations surrounding an individual. My network attributes, however, incorporated: distance, walking speed, day specific pollutant concentrations, ventilation rate (calculated with metabolic rates and physiology for a representative individual), direction and steepness of slope (and its impact on walking speed and breathing rate); thus providing a more accurate assessment of exposure, potentially useful for health related studies.

Having established that walking speed and ventilation rate are both influenced by slope, one technical challenge I overcame was how to accurately estimate the slope of a path, not only differentiating travel across a slope from that along it, but capturing the directionality of the slope, allowing speed and ventilation rate to be computed correctly depending on direction of travel.

Example routes presented in this paper were based on a limited range of sample days, physiology and metabolic rates, and assumed traffic conditions for the morning rush hour (08:00-09:00). The method, however, sets out the parameters needed to calculate time and person specific least-polluted routes. As low cost sensor network technology develops it is conceivable that the approach described in this paper could be developed into a real time application that could help users minimise their exposure to air pollution. Methods here could also be used in other contexts, such as planning routes for new cycle lanes. It is in planning contexts such as this that the greatest impact on reducing journey-time exposure to pollution is perhaps most likely to occur.

Links to my other work

This work was strongly influenced by my previous paper (Davies and Whyatt, 2009). The principles learnt earlier, were adapted into a new methodology that enabled modelling a greater complexity of elements affecting exposure, and allowing modelling to take place at the city scale.

The dispersion model used in this piece of research was subsequently adapted and used to provide inputs to the analysis I undertook for the paper 'A futures-based analysis for urban air quality remediation' (Pugh et al., 2012) where I estimated journey-time exposure for a selection of pre-determined walking routes from a proposed future urban development.

Journal standing and citations

Science of the Total Environment is an international journal, publishing articles which combine two or more of the following overlapping spheres: atmosphere, hydrosphere, biosphere, lithosphere, and anthroposphere. This was therefore a good fit for a study focusing on air pollution and human health. It has an impact factor of 4.610.

To date this article has 13 citations.

DAVIES, G., HALE, J. & SADLER, J. Modelling functional connectivity pathways for bats in urban landscapes. Proceedings of the GIS Research UK 20th Annual Conference. Lancaster University, Lancaster, 2012. 95-100.

HALE, J. D., FAIRBRASS, A. J., MATTHEWS, T. J., DAVIES, G. & SADLER, J. P. 2015. The ecological impact of city lighting scenarios: exploring gap crossing thresholds for urban bats. *Global Change Biology,* 21, 2467-2478.

Summary

I have paired these articles as a single submission, the first being a published conference paper which demonstrates my contribution towards the subsequent paper in Global Change Biology. This work was born out of a large collaborative EPSRC-funded research project 'Urban Futures' (Boyko et al., 2012) which was organised into work packages. I contributed towards research in both the air quality (Pugh et al., 2012) and ecology (Hale et al., 2013, Hale et al., 2015, Davies et al., 2012) work packages.

These papers both considered the ecological impact of lighting on bat crossing behaviour in urban environments. The method was built upon field survey results and a subsequent binomial model of bat movement behaviour in relation in artificial light and tree cover – this aspect of the work was led by James Hale at the University of Birmingham. The first of these two papers focuses upon the land cover types responsible for delivering functional connectivity. The second develops city wide scenarios for brighter street lighting futures and assesses the impact that this may have on accessible land cover.

Contribution to field

This research not only enables barriers to bat movement in urban environments to be identified, but also potential solutions to be explored, such as key areas where a lowering of light levels could significantly increase the functional connectivity of the bats' habitat.

This study improved understanding of the impact of lighting on functional connectivity for bats. We based the model for bat movement on empirical data, which, is highly valuable in ensuring that model outcomes are realistic. These data were used to develop a statistical model of gap crossing behaviour, which I then developed into a spatial model using the cost distance tool in ArcGIS.

The cost distance analysis used high resolution ($1m^2$) inputs, including tree cover derived from LiDAR, and lighting data that was derived through a new method we developed and published in Hale et al. (2013). Combining these new datasets, with a detailed analysis mask, and importantly an empirical model, allowed us to provide new insights into the gap crossing behaviour of urban bats and the impact that had on the functional connectivity of their habitats. It provided a method which could be applied in planning processes to assess the impact that adding or removing trees or types of lighting may have on the functional connectivity of bat habitats. It also enabled an assessment of the landscape types that contribute to functional connectivity.

This work has been widely cited primarily in relation to bat crossing behaviour (for example: Le Roux et al., 2018; Pauwels et al., 2019; Pinaud et al., 2017; Bhardwaj et al., 2017; Azam et al., 2015) and the subsequent impact on foraging behaviour (for example: Medinas et al., 2019; Azam et al., 2018; Lewanzik & Voight, 2017).

Links to my other work
The lighting (lux) layer used in this analysis was generated from aerial night-time photography during earlier work undertaken with Hale et al. (2013).

The application of least-cost paths, at high resolution and with a detailed mask of traversable space, builds on previous work reported in Davies & Whyatt (2009).

Journal standing and citations
The GIS Research UK conference is an international conference focusing on academic GIS research.

This conference paper outlines my role in the research development for the subsequent paper: 'The ecological impact of city lighting: exploring thresholds of functional habitat connectivity for urban bats'. This published conference paper has received 2 citations, with many more citations relating to the journal article to which this paper subsequently contributed.

Global Change Biology is an international journal focusing on current environmental changes that impact biological systems globally. It has been ranked as the third most cited journal in climate change research. It has an impact factor of 8.997.

To date this article has 55 citations.

The article's publication was also covered in the international press including the Huffington Post and Daily Mail (Woollaston 2015, Freeman 2015).

DAVIES, G., FRAUSIN, G. & PARRY, L. 2017. Are there food deserts in rainforest cities? *Annals of the American Association of Geographers,* 107, 794-811.

Summary
This study was part of a larger ESRC-funded project exploring urban food insecurity in the Brazilian Amazon. The paper investigates whether food deserts are present in a rain forest setting, exploring three small towns and sample areas of two larger towns within the Brazilian state of Amazonas. Food deserts are defined as areas with insufficient access to affordable healthy food. Originally a concept born in the UK and USA, food deserts have rarely been investigated in the global south. Most

previous food desert studies define food accessibility in terms of access to the nearest grocery store such as a supermarket. In a context where supermarkets are scarce and food is purchased from a variety of very small shops, I developed a novel approach to defining food accessibility and food deserts. This approach computed the combined access to key products sourced from a variety of shops.

Food deserts were identified by first computing the distance from the nearest location selling each of the individual surveyed products. Distances were computed by creating cost distance surfaces, using a mask representing traversable space. This approach was chosen over computing network distances as it later allowed layers for each product to be reclassified and combined using map overlay. Map overlay was used to add together the number of available products within each of the following categories: staples, animal protein, fruit and vegetables. These groups of products were then reclassified into surfaces which indicated where a sufficient range of products were available for a healthy diet. These were finally combined using map overlay to identify areas with or without sufficient access to all food groups.

While it was concluded that food deserts were widely present within the study area investigated, the research also highlighted the limitations of conventional food desert definitions and their failure to account for alternative food sourcing. This is potentially significant within this study region where fruit and vegetables are frequently grown at home or picked from publicly accessible trees. This highlights an opportunity for further research into the accessibility of non-retail fruit and vegetable provision.

Contribution to field

Whilst food deserts have been widely studied in western contexts where supermarkets dominate food purchasing behaviour, in this study we sought to test the applicability of this concept in a very different geographic setting, where supermarkets are yet to penetrate and food is still purchased from a network of small shops.

We began by conducting a large survey of shops gathering data on availability and price of a number of healthy food products important to local diets. This provided us with a uniquely rich dataset for the study. While many examples of cost distance analysis have used map overlay to create input cost surfaces, I reversed this principle to use multiple cost distance surfaces as inputs to raster map overlay. The cost distance surfaces provided a realistic modelling of movement through space and measurements of distance from the nearest shop selling any one of the given products surveyed. The method I developed enabled layers to be combined and thresholds defined for different categories of food. When combined together these not only provided a definition of food deserts, but also which category of food was unavailable for any given area.

The study provided enhanced understanding of food availability and affordability in urban centres of the Brazilian Amazon, but also provided a new methodology for exploring food deserts in contexts where food is sourced from networks of small providers. It also begins to explore some of the non-retail food sourcing strategies that may be significant and the impact these may have on accurate definitions of food deserts.

Links to my other work

Many of the techniques used to model food deserts in this study were informed by my earlier work. Combining detailed analysis masks with cost distance surfaces to model movement through space was applied both in my earlier study of journey-time exposure to air pollution (Davies & Whyatt, 2009) and the study of the impact of lighting on gap crossing behaviour for bats (Davies et al, 2012; Hale et al, 2015). Likewise, this work draws from that which I developed in Hale et al (2015) to model areas that were functionally connected to ponds (feeding sites for bats). This concept was in turn the basic building block upon which a new model for defining access to multiple required food sources was developed.

Journal standing and citations

Annals of the American Association of Geographers is an international journal publishing papers that make an important contribution to geographic knowledge. It has an impact factor of 2.097, ranking 7th out of 84 international geography journals

To date this article has 5 citations

PARRY, L., DAVIES, G., ALMEIDA, O., FRAUSIN, G., DE MORAÉS, A., RIVERO, S., FILIZOLA, N. & TORRES, P. 2018. Social vulnerability to climatic shocks is shaped by urban accessibility. *Annals of the American Association of Geographers,* 108, 125-143.

Summary

This paper was also part of the larger ESRC-funded project exploring urban food insecurity in the Brazilian Amazon. The purpose of this paper was to provide new understanding of the impact of spatial accessibility on social vulnerability to extreme climatic events in the Brazilian Amazon. Here emphasis was placed on understanding why some urban centres have greater social vulnerability to floods and droughts. However, to understand the impact of spatial accessibility we first needed a means by which to measure travel distances between urban centres. This was achieved by developing a travel network for the region, from which a remoteness index was generated. This was then used to test whether accessibility explained differences in social sensitivity (demography, sanitation, ethnicity, health, education, rurality), adaptive capacity (health care provision, education provision, urban population growth, poverty), and food system sensitivity (based on a food price survey). One of the key conclusions was that remote urban centres have higher social vulnerability.

Technical contribution

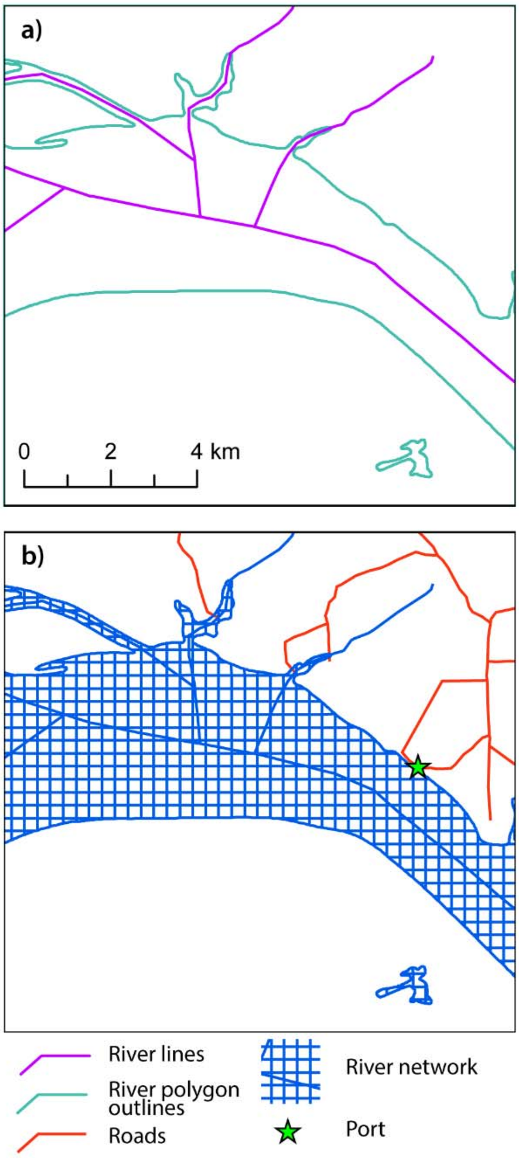

Figure 1: a) river line and polygon outline features selected for inclusion in network dataset; b) multimodal network including 300m fishnet to enable river crossing, roads and ports as points of connection between road and river

My contribution to this paper was the development of a multi-modal river and road network, and subsequent network analysis to compute the remoteness index. The network dataset was created for six states within the Brazilian Amazon, covering an area of 3.6 million km^2 including 605,000km of rivers at a scale of 1:250,000, extracted from Millenium Map Hidrografia data. Only named rivers were selected, in order to remove smaller tributaries not used for navigation. This filter was crossed checked with smaller scale data for which stream order data was available. The primary challenge of this dataset was how to incorporate rivers into the network that were initially represented as polygons (see Figure 1a). Networks in GIS are represented by lines which do not account for the width of a feature. As rivers were often several kilometres wide, the network structure needed to accommodate movement across a river as movement well as along a river. This was achieved by creating fishnet of lines spaced 300m apart, which were clipped to the extent of the river polygons (see Figure 1b). These lines provided a means by which to cross from one side of the river to another. They also enabled shorter routes to be taken around bends rather than assuming boats will always travel at the location of the river centreline. River polygon outlines were converted to line features and merged with the smaller rivers already represented as lines, and the 300m fishnet, before cleaning the topology of the new river dataset.

River crossing (bridge or ferry) also needed to be accounted for within the road elements of the network. Breaks in the road data often occurred even where bridges existed. Careful identification and manual editing of the road data was required to accurately account for possible river crossings. Aerial photography, where available (via ArcGIS or Google Earth), and Google Street View were used as a guide to establish whether bridges were present, and where bridges were absent, whether ferry crossings were present. Connections between the road and river network were only possible at the location of ports. Cost impedance assigned at ports ensured that wait times for passengers or loading times for goods were accounted for and excess switching between road and river elements of the network was avoided.

Once the network dataset was created, I used this to calculate distances from every urban centre within the Brazilian Amazon to the nearest city at each level of the urban hierarchy. These distances were then weighted to generate the remoteness index used in the subsequent analysis within this paper. Further information on the weightings for the remoteness index can be found in the supplementary material provided alongside the submitted publication for Parry et al (2018).

Contribution to field

The methodology developed to incorporate wide rivers into models for riverine travel is new and could potentially be used to model movement through large river networks in other parts of the world.

The remoteness index, when combined with variables used to estimate sensitivity and adaptive capacity, provided unique insights into the underlying spatial basis for the social vulnerability to climate shocks.

Links to my other work

While the scales and approaches presented in this paper are very different from those used to assess food deserts in Davies et al (2017), many of the underlying principles are similar. Here, rather than access to shops providing different food products it is towns providing different levels of service provision that are of relevance.

Journal standing and citations

Annals of the American Association of Geographers is an international journal publishing papers that make an important contribution to geographic knowledge. It has an impact factor of 2.097, ranking 7th out of 84 international geography journals

To date this article has 6 citations

DAVIES, G., DIXON, J., TREDOUX, C., WHYATT, J.D., HUCK, J., STURGEON, B., HOCKING, B., JARMAN, N., BRYAN, D. 2019. Networks of Dis(connection): Mobility practices, tertiary streets and sectarian divisions in north Belfast. ***Annals of the American Association of Geographers.*** **(Published online 30/5/2019)**

Summary

This paper is part of a large ESRC interdisciplinary research project that explored the impact of segregation on the everyday mobility of people in North Belfast (Dixon et al., 2019; Huck et al., 2019, Hocking et al., 2019, Hocking et al., 2018). In Northern Ireland there have been long-standing tensions between Protestant and Catholic communities. The paper explores the ways in which residential segregation, especially within networks of 'tertiary streets' (small residential streets) impacts residents' mobility. The research builds upon the concept of T-communities, first developed by Grannis (1998). T-communities are defined as interconnecting tertiary street networks that terminate when they reach either a main road or other physical or physiological barrier. Further description of the creation of T-communities can be found in the supplementary material provided alongside the submitted paper Davies et al (2019).

A network dataset was created using road data from Ordnance Survey Northern Ireland (OSNI), to which additional connecting paths were captured using OSNI basemaps, Google Maps and aerial photography as a guide. T-communities were created using the service area function within ArcGIS' network analyst. Main roads and other features such as peace walls were included as barriers, which defined the outer limits of the T-communities. Main roads were broken into sections where a major junction was reached or there was a known community divide. Community affiliation was then assigned both to the T-communities and to sections of main road. Movement data was taken from GPS tracks collected by 185 residents from across both communities. These tracks were cleaned and divided into distinct routes and stops. These data were then used to calculate the amount of time spent moving within areas of similar community affiliation (ingroup), areas not clearly associated with either community (mixed), or areas of opposing community affiliation (out group). The amount of time spent within T-communities or along sections of main road was also calculated. Further exploration of the data considered variations in behaviour based on mode of transport or gender.

The paper concluded that residents were significantly more likely to spend time moving within ingroup areas, and that this was especially true for movement within T-communities. Time spent within outgroup areas was more likely to be along sections of main road than within T-communities and this time was more likely to be within a vehicle than on foot. Women were no more likely than men to move within outgroup space. The study also explored the extent to which the concept of T-communities

could successfully be adapted to work at a very different scale, and in a different geographic context to that for which it was originally designed.

Contribution to field

While residential segregation is relatively well researched, few studies have explored the impact of segregation on mobility, which is the context for this study. A uniquely rich set of GPS tracks captured through a year-long field campaign allowed us to focus on segregation of people's every day movements, rather than residential segregation which is already relatively well understood.

Most previous studies have relied upon administrative units such as census geography to define neighbourhoods. We however, highlight the limitation of this approach and develop the concept of T-communities to provide more meaningful geographies that reflect the spaces in which people move on an everyday basis. As the T-community concept originally conceived by Grannis (1998), was designed to work for large cities with grid plan layouts, we developed a method to adapt this to work for smaller areas and less regular street layouts, proving the concept to be scalable and transferable to other contexts. In adapting the concept we maintained its key principle of connectivity.

The analysis provided uniquely detailed insight into residents' movements within north Belfast and the ways in which segregation affects people's every day mobility.

Links to my other work

An additional related paper (Dixon et al., 2019) made further use of the GPS tracks to evaluate the number of locations visited in different types of group space, and the time spent in spaces of different community affiliation. While the track data revealed high levels of segregation in terms of limited use of facilities, public spaces and paths within outgroup areas, use of shared spaces was still evident, with Catholics found to spend more time in shared spaces than Protestants. I undertook the spatial analysis for this additional paper.

Journal standing and citations

Annals of the American Association of Geographers is an international journal publishing papers that make an important contribution to geographic knowledge. It has an impact factor of 2.097, ranking 7th out of 84 international geography journals

Full list of my publications to date

Papers submitted for consideration for PhD by Published Work are marked *.

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Critical review

Introduction

There are three key ways in which distance (or other costs) can be modelled using GIS. The first is the Euclidean (straight-line) distance between two features. This is useful for simple measurements or for creating fixed boundaries around features (Mitchell, 1999). This approach, however, fails to account for the many geographic factors which will influence movements through space and therefore the true distances or cost of movement between any given set of locations. Since Euclidean distances cannot replicate the complexities of actual routes they tend to under-estimate distances between origins and destinations and overestimate areas served by a given facility (Gibson et al., 2011; Gupta et al., 2016). Distance or cost between features can also be calculated through a network (Mitchell, 1999). Networks have a theoretical basis in graph theory and topology (Curtin, 2016), consisting of edges, interconnected by junctions, through which resources can flow (Heywood et al., 2011) and are useful when modelling movements that are essentially constrained by geographies that can meaningfully be represented by sets of linear features such as: roads, paths, rivers, or utility pipes (Heywood et al., 2011; Mitchell, 1999). Not all movement can however be modelled in this way (Choi et al., 2014). For example, movement across open terrain cannot be modelled using network analysis (Balstrøm, 2002). The final option is, therefore, to measure cost of movement through a raster surface. Raster models can be used to represent data that varies continuously across space, and can include cost-impedance for movement (Mulrooney et al., 2017). Cost distance rasters differ from Euclidean distance equivalents, since they account for differing 'costs' of movement across space, often referred to as friction values. Furthermore, cost distance rasters compute distance travelling around barriers, as represented in an analysis mask, whilst Euclidean distances do not account for masked out areas when calculating distances. Least-cost paths can then be traced through cost-distance surfaces to identify routes of least-accumulated cost to a given destination.

This short review will introduce both network and raster approaches to generating least-cost paths, and other methods of modelling movement. It will explore their technical application and some of the opportunities and challenges presented by these approaches for real world application. Following this review, I will explain how my work using these techniques, contributes to greater understanding of connections or movement through space.

Network analysis

Networks consist of interconnected edges (lines) which are connected by junctions (nodes), through which resources can flow (Brach & Górski, 2014; Curtin, 2007; Mitchell, 1999). Each edge has two junctions, a 'from node' and a 'to node', which enables both connectivity between edges and directionality to be defined. These topological principles of connectivity and directionality are important for determining flow through the network (Devlin et al., 2008). The most common example of a network is a road network, comprised of roads (edges) and junctions through which traffic flows. Other types of network include railways, footpaths, rivers, and utility pipelines (Liao et al., 2016; Mölter & Lindley 2015; Webster et al., 2016). Networks can also be multi-modal, for example, connecting walking, bus and rail networks.

In order to represent real world behaviour in a network a number of assumptions need to be made (Delamater et al., 2012). The first set of assumptions relates to the way in which the topologically structured edges and junctions represent the space and connections through which movement can take place. The accuracy of results generated from network analysis depends upon good spatial representation of network edges e.g. roads, and their connectivity at junctions, for example, clearly distinguishing between fly-overs and street level cross roads (Mitchell, 1999). The second set of assumptions relate to the definition of network attributes. Network attributes determine the resistance to movement within the network and can be applied to edges and\or junctions (Brach & Górski, 2014). The most important of these attributes for determining the impedance of movement through a network is cost. Cost attributes are apportionable along a network edge, meaning that if only a section of the network element is traversed the cost will be apportioned accordingly (ESRI, 2017a). A cost attribute is essential as all network functions involve minimising the accumulated cost of moving through the network, for example, minimising travel time or distance. Descriptor attributes are assigned to the whole of a network edge and contain information such as road name, speed limit etc. These are useful when generating directions and for calculating cost attributes (ESRI, 2017a). Restrictor attributes account for prohibited travel, such as preventing vehicles travelling along pedestrianised streets; setting one-way travel restrictions for traffic, or preventing flow upstream in a river network. Hierarchy attributes break features such as roads into different classes, for example giving greater preference to higher-order roads. This attribute potentially helps speed up processing, however, may lead to less accurate results (ESRI, 2017a). As most network edges have two possible directions of travel, network attributes can be assigned to both directions of flow (ESRI 2017a), thus enabling different impedances to be applied, for example, making it possible to model a boat travelling quicker downstream than upstream. Figure 2 demonstrates the structure of edges and junctions for a road network with associated attributes.

Barriers can also be incorporated into networks, either to prohibit all movement such as in response to a road closure (Devlin et al., 2008) or to add a cost impedance such as the time taken to cross a main road (Mölter & Lindley, 2015). Barriers may take the form of points, lines or polygons. These are potentially useful when modelling response to incidents such as traffic accidents or flooding.

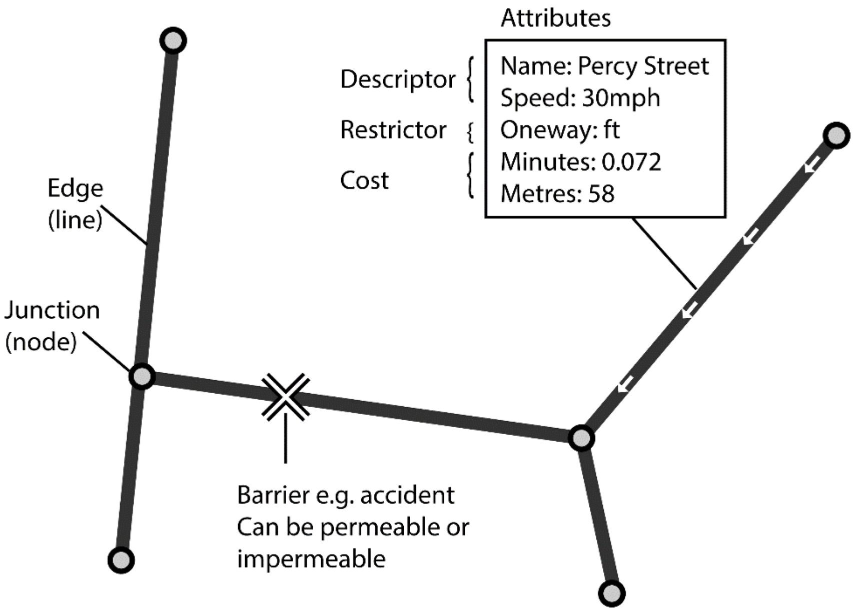

Figure 2: Key elements of a network dataset

There are a number of different types of network operation which can be employed once a network dataset has been created (Bernhardsen, 2002), the most widely used of which is to find the shortest (or least accumulated cost) path between two locations, based on time or distance (Curtin, 2007; Heywood et al., 2011; Gülgen, 2017). There are a number of algorithms that can be used to determine optimal routes (Curtin, 2007) the most common of which is Dijkstra's algorithm (Dijkstra, 1959). This shortest path operation is at the route of many other network operations. The first of these is termed the travelling salesperson problem and is designed for use when multiple stops need to be visited in the most efficient order. This approach combines shortest path operations with the ability to optimally order stops. This is a non-trivial task with 10 stops having 362880 (9×8×7×6×5×4×3×2×1) permutations for stop ordering (Heywood et al., 2011). The shortest path operation can also be extended to find the closest facility. In this case, shortest paths are found from an origin to each possible destination, and the shortest of these solutions is then selected (Curtin, 2007; Verbyla, 2002). This principle can be extended further still to generate a table of shortest paths between all possible origins and destinations, this is referred to as an origin-destination cost matrix (Curtin, 2007). Network operations also include the ability to determine the service area of a given location (Curtin, 2007). Service areas highlight all areas (defined by a polygon area or network edges) that are within a specified cost impedance of a location (ESRI, 2017b).

Network applications

Network analysis can be applied to answer many different types of research question and has been used across a wide range of application areas. One of the most widely recognised applications of network analysis is **routing** (Brach & Górski, 2014), with a vast number of websites now available to assist the general public in finding the fastest route (Wang & Xu, 2011) by car (AA, 2018) or by a selection of travel mode options (Bing, 2018; Google, 2018; TFL, 2018). A few more specialised route finding application exist for limited locations, such as Walkit.com, designed for urban walking with options to select less busy routes as well as shortest routes for a selection of UK cities (Walkit.com, 2018). Bespoke route planning systems have also been developed for more specific purposes, such as a web-based route planner for a public forest in Poland (Brach & Górski 2014). The system developed by Brach & Górski (2014) computed routes between given facilities and attractions by car, bicycle or on foot; with options for shortest route (accounting for 3D distances), fastest route (accounting for 3D distance, slope and road type), or most ‘natural’ route (accounting for travel time, naturalness of road surface, and whether the road was within the forest). While designed to enhance the visitor experience the system also ensured the public were kept away from vulnerable areas. More specialised routing applications have also developed for specific tasks or industries, for example finding optimal routes for waste collection (Bhambulkar, 2011; Malakahmad et al., 2014) or haulage of goods (Devlin et al., 2008; Parsakhoo & Mostafa, 2015).

While most routing analysis is based on a static set of travel speeds, it is possible for network analysis to utilise information on current travel conditions (Google, 2018; Huang & Pan 2007; Stenovec, 2015). Huang & Pan (2007) demonstrate the power of network analysis when combined with other models. They developed an incident response management tool linking a traffic simulation model to the GIS to undertake network analysis, and finally to an incident response optimisation model. The most well-known, time specific, route planning service is within Google Maps (Google, 2018), where using data transmitted from the location services of smart phones, Google are able to analyse the number and speed of cars on the road network at any point in time. This enables routing to account for current traffic conditions, but also provides a history of typical travel times which enables the service to estimate typical journey times for a particular time and day (Stenovec, 2015). Time-varying network datasets are also now available via ArcGIS online, with global road coverage, for use with network analysis in ArcGIS Pro.

Any network and routing operation is, however, only as good as the information represented within the network. Network elements are typically well represented in road databases. Ready to use, topologically structured network elements are however less common for other features such as footpaths or pavements. Routing of pedestrians within network analysis is therefore often poor. The ability of a network dataset to effectively represent the real world is heavily influenced by the accuracy of its network attributes. While distance attributes can be easily calculated, time and other network attributes require additional information. While recent advances in technology such as those employed by Google demonstrate potential for more accurate estimates of travel time, this information has limitations and does not reflect the potential behaviour or requirements of all network users. More complex attributes can be incorporated into a network dataset, representing scenery, facilities on route, weather (Sadeghi-Niaraki et al., 2011) or naturalness (Brach & Górski, 2014), but these examples are rare. Some of these more complex network attributes may also be subjective and difficult to quantify, while others require regular updating or real time data e.g. weather. Varying preferences and behaviours of individual users will also present challenges when trying to model route choice. This is again perhaps a greater challenge for pedestrians than for vehicles, where personal preferences, including perceptions of safety all potentially influence route choice (Walker et al., 2009).

Measuring **accessibility** is another very common application area for network analysis. Many accessibility studies focus around healthcare, identifying gaps in service provision (Delamater et al., 2012; Gibson et al., 2011; Luo and Wang 2003) and in exploring the impact of distance from service provision on uptake of treatment options (Athas et al., 2000; Entwisle et al., 1997). Often associated with health and well-being, access to greenspace has also been widely analysed using network analysis either simply to assess how much of a city or area is served by green space (Gupta et al., 2016; Oh & Jeong 2007), or to examine inequalities in access between different groups of people (Comber et al.,2008; Nicholls, 2001). Accessibility to other services has also been measured using network analysis, such as access to public transport systems (García-Palomares et al., 2013), and services such as post offices (Comber et al., 2009) or libraries (Park, 2012). Similarly, analysis of the connectivity of settlements to each other and to key centres of service provision is important for their development and resilience (Castella et al., 2005; Lee et al., 2013; Webster et al., 2016).

Varying levels of complexity can be added into assessments of accessibility, which help to improve the quality of subsequent results. At the simplest level accessibility can be modelled using buffers with a fixed distance threshold. The main limitation of this approach is that straight-line distances fail to account for impedances to movement and potentially overestimate the extent of the accessible area. This is illustrated by Nicholls (2001) who generated service areas around parks in Bryan, Texas. Nicolls found that the area defined by the network service areas was only half the size of the area defined using straight-line distance buffers. This highlights the potentially significant additional benefit of using network analysis to account for traversability when assessing service accessibility. Fixed distance thresholds are commonly applied to studies of accessibility, for example, Delamater et al. (2012) define 30-minute service areas around acute care hospitals in Michigan to identify underserved areas and Gibson et al. (2001) similarly defined service areas to identify travel times and spatial coverage of health care in the Shaanxi Province of rural China. Simple assumptions about distance thresholds fail to represent gradually decreasing levels of accessibility. There are ways that the challenge of this distance threshold can be addressed. One option is to apply a gravity model which defines nearer areas as having greater accessibility, such as applied by Wang (2011) when modelling access to physicians. Another option is to calculate distance from each location to each facility then examine the probability of service take up. One example of this is a study in New Mexico exploring the impact of patient's distance to radiotherapy units on their likelihood of receiving treatment (Athas et al., 2000). Entwistle et al. (1997) examined how accessibility of family planning clinics affected contraceptive choice in the Nang Rong area of Thailand. Garcia-Palomares et al. (2013) analysed the accessibility of the Madrid metro system, by computing distances through a path network from respondents home addresses to metro stations, and from this a distance decay function was computed for each population group (e.g. elderly, children). In a similar way Park (2012) computed distances through a road network from libraries to home addresses of library users in Lake County, Florida, in order to calculate the average distance that people were prepared to travel to use library services, examining differences in travel distance between different ethnic groups.

Measures of accessibility can also be improved by accounting for travel time rather than purely distance. This may include accounting for factors such as road composition, seasonal roads (Entwisle et al., 1997), or pedestrian friendly roads (Nicholls, 2001). It is also important for some facilities, such as green space, to measure distance to access points (e.g. park entrances) rather than boundaries (Nicholls, 2001). While most origin and destinations can be defined as a simple point feature e.g. address or service, larger features represented as polygons may need to be represented by specified access points or entrances in order to accurately reflect the cost of reaching them.

In addition to access to services, connectivity of settlements to each other and to key centres of service provision is important for their development and resilience (Castella et al., 2005; Lee et al., 2013; Webster et al., 2016). Lee et al. (2013) consider this in the context of integrated rural tourism planning in the Republic of Korea using network analysis to explore not only distances to other tourist villages, but also which tourist villages are located on routes linking other tourist centres. Through their work they demonstrated the applicability of centrality indices for evaluating accessibility and level of influence on surrounding villages. A more comprehensive assessment of access and remoteness was carried out by Castella et al. (2005) to examine the relationship between village accessibility and land use in a mountainous province of Northern Vietnam. Here, travel was through a road network, with different travel times calculated depending on type of vehicle and type of road. Accessibility of each village was then scored based upon different indices including: number of teachers and doctors within 1 hour; travel time to the nearest village, health service, market place; and average time to the district and provincial administrative centres. They were then able to assess land use and opportunities for development in relation to village accessibility.

Network analysis can be also used to help model **exposure** during journeys, with exposure-related applications commonly focusing on exposure to air pollution (Hasenfratz et al., 2015; Hatzopoulou et al., 2013; Hertel et al., 2008) and food outlets (Burgoine & Monsivais, 2013; Harrison et al., 2014). Studies aimed at assessing the potential to reduce journey-time exposure to air pollution have been developed for walking (Mölter & Lindley 2015; Walkit.com, 2018), cycling (Hatzopoulou et al., 2013; Hertel et al., 2008) and varying travel modes (Hasenfratz et al., 2015). Least-polluted routes are typically defined by multiplying the length of network segment with the mean pollution concentration (typically NO_2 or particulates) of that segment to represent ambient exposure (Hasenfratz et al., 2015; Hatzopoulou et al., 2013; Mölter & Lindley, 2015). Differences in both journey-time exposure and distance can be compared between the shortest and least-polluted routes generated. The potential of least-polluted routes to reduce journey time exposure varied between studies from 7.1% in Hasenfratz et al's (2015) study in Zurich, 4% in Hatzopoulou et al's (2013) study in Montreal and 1.5% for half of the routes in Mölter & Lindley's (2015) study in Greater Manchester. These variations in potential for exposure reduction can be explained by different street configurations; pollution characteristics; and choice of origins and destinations within the studies in question.

Exposure to the food environment (type of food outlets) is thought to relate to dietary behaviour and therefore health (Burgoine & Monsivais 2013). Recognising that exposure to food outlets during commuting journeys to work or school may be equally or more significant that outlets near to home, work, or school, some researchers have used network analysis to define commuting routes. They then determine the type of food outlets a given individual may be exposed to on such routes (Burgoine & Monsivais 2013; Harrison et al., 2014). Harrison et al. (2014), however, used GPS tracks in addition to GIS modelled routes, to identify routes taken by participants; finding that the shortest routes generated using network analysis typically underestimated journey length by 12%. They also identified that participants generally walked along quieter roads. This understanding of human behaviour is important when considering the example of journey-time exposure to air pollution. If people are already choosing quieter routes it is likely that to some extent they are already avoiding the most polluted routes. The potential reduction in exposure to air pollution between the routes people generally take and least-polluted routes may be smaller than comparisons between shortest routes with least-polluted routes.

Many studies highlight the benefit of computing network distances (Gibson et al., 2011; Harrison et al., 2014; Nicholls 2001; Singleton, 2014; Bejleri et al., 2011). Bejleri et al. (2011) take this comparison one step further, comparing walking distances for school journeys between straight-line; road network based; and a walking network adjusted for barriers to walking, such as roads without pavements, and facilitators to walking such as informal paths. These results showed considerable variations in the area accessible on foot within half a mile of given schools. Amongst other considerations their approach reinforces the importance of using appropriate footpath networks for walking studies (Duncan & Mummery, 2007; García-Palomares et al., 2013; Hasenfratz et al., 2015; Oh & Jeong, 2007). Some studies do however rely on existing road networks as a surrogate for path networks (Comber et al., 2008; Harrison et al., 2014).

It is evident that road networks are the most common type of network dataset, and that sometimes, as discussed above, these are developed further to create path networks .

Rail networks are also sometimes considered (MartÍn et al., 2004; Singleton, 2014; Wang, 2000). While some papers consider more than one type of network, (Hasenfratz et al., 2015; MartÍn et al., 2004; Singleton, 2014) there are few examples of use of multi-modal networks, yet it is clear that these underpin common journey planning applications (Google, 2018; TFL, 2018). Likewise, only a few examples exist in the literature of river or utility networks (Gülgen, 2017; Liao et al., 2016; Webster et al., 2016). Gulgen (2017) uses a river network dataset to demonstrate a network method for defining stream order. Liao et al. (2106) use a drainage system network to trace and track pollution within the system. Webster et al. (2016) use a river network to model travel by boat between different population centres within the Peruvian Amazon.

For the majority of network analysis studies, the cost attribute used is either distance or time. Cost attributes can, however, represent a wide range of characteristics. For example, Brach & Gorski (2014) created a network attribute for naturalness of route for tourists within a forest park. Air pollution concentrations have also been used as cost attributes to help determine least-polluted routes (Hasenfratz, et al., 2015; Mölter & Lindley, 2015). Sadeghi-Niaraki et al. (2011) also demonstrate the potential to incorporate a wider range of model variables when determining route choice.

This section has highlighted not only some of the breadth of applications for network analysis, but some of the challenges and limitations of simulating real world behaviour through a set of network elements and attributes. While no network dataset will ever be able to fully model the real-world, a balance needs to be found between over-simplification and the complexities of sourcing and incorporating more accurate and potentially time-sensitive variables into the network.

Raster cost distance analysis

While network analysis is effective for modelling movement through space when that movement can realistically be constrained to a series of edges and nodes, modelling movement and connections through open spaces, such as mountainous terrain, requires a different approach (Balstrøm, 2002; Choi et al., 2014). This is particularly useful for applications such as animal movement and habitat connectivity (Ganskopp et al., 2000; Halpin & Bunn, 2000) where movement is not limited to a set of connected linear features. Within a raster model the area is represented by a continuous surface of pixels (Mulrooney et al., 2017).

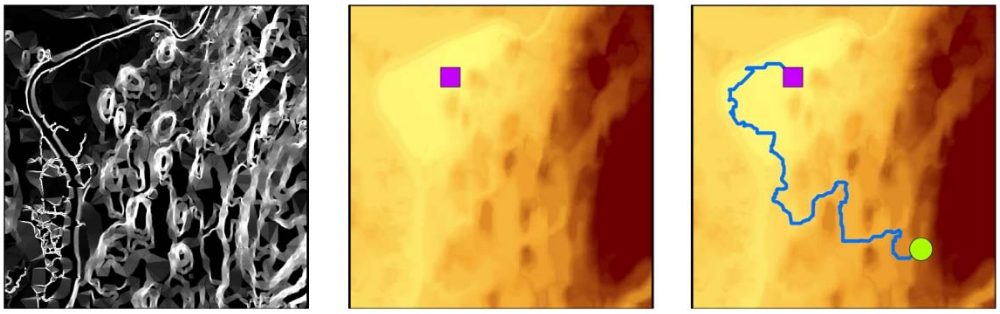

Figure 3: Key stages in least-cost path analysis

As illustrated in Figure 3 there are three key stages for defining a least cost path using a raster approach.

The first requirement is a cost (friction) surface representing cost of movement through space (Etherington, 2016). The friction or cost surface used in the analysis may represent distance, time, monetary cost or other impedance values (Douglas, 1994). The example in Figure 3 uses slope as the cost input and the subsequent analysis seeks to minimise the accumulated slope angle traversed. Often the input cost raster is derived from a composite of inputs representing relevant criteria and combined using map overlay (De Smith et al., 2007).

The next step is the creation of a cost distance surface. This represents the least accumulated cost from an origin, based upon the values in the cost surface (Bernhardsen, 2002, Collischonn & Pilar 2000, Verbyla, 2002). This is achieved using a spreading algorithm which searches the eight neighbouring cells, assigning an accumulated cost to each cell which does not already have a value (Collischonn & Pilar, 2000). This cost distance raster is accompanied by a backlink raster which assigns a number to each cell indicating the lowest cost direction to the nearest source (Lee & Stucky, 1998; Webster et al., 2016).

The final step, if desired, is to compute a least cost path to a specified destination. By combining distance with the accumulated cost represented in the cost distance surface, the optimal path to the destination is determined, minimising the accumulated cost (Bernhardsen, 2002; Verbyla, 2002).

Cost distance applications

The majority of studies using least-cost distance analysis fall within ecology, where it is commonly applied to model animal dispersal and migration (Epps et al., 2007; Etherington et al., 2014; Ray et al., 2002; Wang et al., 2009); and functional landscape connectivity (Adriaensen et al., 2003; Chardon et al., 2003; Janin et al., 2009; Marulli & Mallarach 2005; Moqanaki & Cushman 2016; Richard & Armstrong, 2010). Least-cost path analysis is used to evaluate potential animal movement through the landscape, based upon the cumulative cost of movement (Sawyer et al., 2011). A surface representing cost of movement is typically generated by applying values of favourability/permeability to different landscape features, assigning low cost values to highly favoured features and high costs to less favourable or inhospitable features (Perović et al., 2010; Ray et al., 2002; Singleton et al., 2002). This favourability may represent energy expenditure, risk of mortality or other factors which hinder or facilitate movement (Sawyer et al., 2011).

Costs assigned to different landscape features are often based on expert opinion (Epps et al., 2007; Etherington et al., 2014; Gonzales & Gergel, 2007; Singleton et al., 2002). However, there are arguments for, where possible, using empirical evidence of species behaviour to determine costs (Richard & Armstrong, 2010, Etherington, 2016; Sawyer et al., 2011). This is illustrated in an example using least cost path analysis to predict road crossing behaviours for mammals (Leoniak et al., 2012). This study used a mixture of expert opinion, literature, and empirical evidence in the form of observations of fisher cats. Resulting predications proved accurate for fisher cats, for whom empirical evidence existed and bob cats, however, not for other species such as black bears. This suggests that species relevant observations improve model accuracy (Leoniak et al., 2012). In some instances multiple different cost-surface representations are generated, then compared with empirical evidence to find the best fit (Epps et al., 2007; Etherington et al., 2014; Wang et al., 2009). While this approach has shown improvements in fit to empirical data, creating multiple representations is computationally expensive (Driezen et al., 2007, Etherington et al., 2014; Janin et al., 2009).

Even the best least-cost model will always be limited in the extent to which it can truly model animal behaviour. For example, in their study of hedgehog movements, Driezen et al. (2007) identified that tracked routes taken by hedgehogs were often not the best routes. While this may be due to other factors such as foraging or predator avoidance, it may also reflect the fact that hedgehogs make their choices based on limited information (Driezen et al., 2007). Animals may also find areas of high quality micro-habitats within areas where habitat at the macro-scale appears unsuitable (Sawyer et al., 2011). While least cost path analysis is useful for understanding animal movement, it cannot incorporate everything and needs to be considered as part of a wider understanding of landscape conservation (Sawyer et al., 2011). Care needs to be taken not only with the cost values assigned, but other patterns of behaviour. For example, Richard & Armstrong (2010) caution that with least-cost path analysis it can be easy to assume the cumulative effect of several shorter gap crossings is equivalent to one longer gap crossing, but for many species, such as the robins they modelled, this is not the case.

Habitat fragmentation is widely recognised as a threat to biodiversity (Driezen et al., 2007). Least-cost analysis has the potential to help model the relationship between landscape characteristics and their impact on functional connectivity for a given species. The ecological assumptions underpinning any least-cost model of functional landscape connectivity are however critical to the accuracy of the results derived (Adriaensen et al., 2003), with resistance values often based on expert opinion that is subjective (Driezen et al., 2007; Etherington., 2016). Results are also sensitive to the quality of the input data. Often remotely sensed habitat information is relied upon, with limited assessment of its appropriateness (Sawyer et al., 2011). Even fine scale data inaccuracies can significantly impact the effectiveness of the least-cost model. For example, "a tree line on one side of a road, and not on top of the road or crossing it at one point, may have a profound effect on the resulting cost map" (Adriaensen et al., 2003: pg 238). One key benefit of least-cost distance analysis, is the ability to test species response to landscape management (Richard & Armstrong, 2010), or assess the impact of current structure (e.g. highways) on landscape permeability (Singleton et al., 2002).

While the most common applications of least cost path analysis are within the field of ecology, it has also been applied in other contexts including defining optimum routes for new infrastructure such as roads (Atkinson et al., 2005; Effat & Hassan, 2013; Erdem, 2014; Saha et al., 2005), power supply (Bagli et al., 2011; Kosyakov & Sadykov, 2015), or finding optimum routes through open terrain for people (Balstrøm, 2002; Lee & Stucky, 1998; Jobe & White, 2009) or livestock (Ganskopp et al., 2000). This concept has been expanded to be used in evacuation planning for tsunamis (Fraser et al., 2014, Wood & Schmidtlein 2012), and to measure accessibility, such as accessibility of food outlets (Mulrooney et al., 2017), access to markets in the Peruvian Amazon (Webster et al., 2016) and creation of a global map of travel times to cities (Weiss et al., 2018).

Many of the case studies exploring the routing of new infrastructure used multi-criteria evaluation (MCE) to create a cost surface from a variety of weighted inputs. Often multiple different scenarios are created, with different inputs or weightings used to generate a number of alternative routes. For example, Bagli et al. (2011) created different weighted scenarios optimising new paths for power lines for economic criteria, human health or a combination of health and economic factors. Similarly, Effat & Hassan (2013) weighted different road building scenarios using environmental factors, engineering factors, or a hybrid of both, considering factors such as elevation, land cover, roads, natural protectorates and archaeological sites. Many others have also used MCE analysis to create input cost surfaces for their analysis (Atkinson et al., 2005; Erdem 2014; Saha et al., 2005). Alternative scenarios can also be used to test variations across time or scale. Fraser et al. (2014) ran several versions of their evacuation model optimised for different times of day, designed to reflect differences in the population expected to be present at those times of day, or days of the week. Meanwhile, Wood & Schmidtlein (2012) tested different modelling approaches, data resolutions, and travel speed assumptions.

As with the ecological case studies highlighted earlier, model assumptions often have to rely on existing literature or expert opinion. Few studies have empirical data available that relates directly to the study in question, yet the accuracy of any least-cost model depends on appropriate cost values being assigned (Atkinson et al., 2005). The use of GPS tracks to monitor actual cattle movement enabled Ganskopp et al.

(2000) to more accurately determine slope thresholds that cattle would tend to avoid. These data also enabled them to validate their model, discovering that cattle typically tended towards the least-cost routes. Similarly, Balstrom (2002) measured walking speeds on slopes of varying steepness to guide the time impedance over slopes of different gradients.

One of the key considerations when undertaking analysis of raster least-cost paths is the resolution at which the model is run. One of the main trade-offs when choosing resolution is accuracy versus processing speed (Atkinson, et al., 2005; Etherington, et al., 2014). Ideally cost path analysis should be undertaken with small grid cells that represent the width of the smallest relevant feature within the landscape (Adriaensen, et al., 2003), with higher resolution providing greater accuracy (Greenberg, et al., 2011). In reality, however, this may not be feasible as processing speeds may be too slow to be manageable, as found by Gonzales & Gergel (2007) who had to increase the cell size for their analysis of invasive species management. In contrast, when modelling the cost distribution of connecting new customers to an urban power grid, Kosyakov and Sadykov (2015) concluded that while model runs took several hours to run at $2m^2$ resolution, lower resolution analysis compromised results. Resolution also needs to be appropriate to the scale of the analysis and size of the study area being explored (Greenberg et al., 2011).

The same resolution may not be appropriate across different scales. For example, Weiss et al. (2018) modelled city access globally at a resolution of $1km^2$, appropriate for global scale analysis and where accuracy of less than $1km^2$ may add little value. In contrast Wood (2003) modelled evacuation routes from a tsunami at a resolution of $1m^2$ over an area of coast approximately 20 x $4km^2$. Wood (2003) explored their analysis further testing sensitivity to different resolutions, discovering significant differences in travel times when the slope variable was resampled to $10m^2$ or $30m^2$. Ultimately the resolution needs to be appropriate to the landscape and types of movement being modelled (Balstrøm, 2002; Mulrooney et al., 2017). A key constraint on resolution and subsequently accuracy of any model is the resolution of available data. Erdem (2014) reports availability of freely available elevation data (ASTER DEM – $30m^2$) as a constraining factor in his use of least-cost path analysis to find a route for a new highway. Ray et al. (2002), who undertook their analysis at $10m^2$ resolution, similarly report lack of high resolution data as a limitation when investigating habitat permeability for the common toad and the alpine newt.

The final key challenge, associated in part with resolution, is how to represent linear features, such as river crossings (Balstrøm, 2002; Jobe & White). Care needs to be taken to ensure that linear features do not disappear when converted to raster, or develop penetrable gaps which may break a potential barrier to movement. Options to overcome this challenge include either conversion to polygon, such as by buffering, prior to incorporating into a raster model (Adriaensen, et al., 2003), or application of a gap filling process (Etherington, 2016).

Other modelling techniques

While the network analysis and raster least-cost approaches already discussed are two of the key ways to model movement, alternative approaches have also been developed and are cited within current literature. One widely referenced model is that of random walks. Here the basic concept is that an individual takes its next step at random, in any direction, and uninfluenced by previous movement. Refinements to the random walk model, however, include prioritising forward motion (correlated random walk), or movement towards a given end point (biased random walk) (Codling et al, 2008). Ahearn et al (2017) expand further on this concept, introducing the idea of a context-sensitive correlated random walk which integrates environmental context, using real movement data captured with a GPS to develop parameters. Random walks are the basis behind many agent-based modelling simulations of movement toward destinations (Technitis et al, 2015) as well as circuit theory (McRae, 2008).

McRae et al (2008) introduced circuit theory to assess ecological connectivity. This is based on the theory of electrical circuits. The key concept behind this theory is that connectivity increases when multiple pathways are available. The theory can be applied to model movement and dispersal probabilities of random walkers through a complex landscape (McRae et al, 2008). The resulting 'resistance distance' not only considers the minimum cost between two nodes, but also the cost and availability of alternative routes. Circuit theory therefore complements more conventional least-cost distance measurements both, by considering all possible pathways, and by assuming a random walk whereby it is not assumed that the individual who is moving has complete knowledge of the landscape before they move (McRae et al, 2008). Computing resistance distance between multiple patches can, however, be very computationally intensive unless a cut-off distance is applied (Avon & Bergès, 2016). Circuit theory and resistance distance may be useful in contexts such as that identified by Driezen et al. (2007) when routes taken by hedgehogs did not follow least-cost routes, due to the presumed limited information the hedgehog has about the landscape through which it was moving.

By predicting probability of movement through edges and nodes using circuit theory, nodes through which a high proportion of potential routes need to pass can be identified as 'pinch points'. If severed these 'pinch points' can have significant impacts on connectivity and are therefore useful points to identify for conservation purposes (Lechner et al, 2017; McRae et al, 2008). In comparing least-cost distance and resistance distances when prioritising habitat patches for landscape connectivity Avon & Bergès (2016) found that results were almost the same, and therefore recommended use of least-cost paths in the first instance, before deciding whether to refine results using resistance distances to quantify patch contribution to dispersal fluxes. A set of tools have been released in CircuitScape and LinkageMapper which facilitate the application of circuit theory for exploring pathways across a landscape (McRae et al, 2019).

Further recognising the complexities of species dispersal Bocedi et al (2014) developed the RangeShifter application which integrates population dynamics into the modelling of movement, considering distinct stages of emigration, transfer and settlement. The individual based modelling approach that they adopt is able to incorporate traits associated with different stages of life history, and for example ensure that males only settle in patches that females have already settled in (Bocedi et al, 2014). One key benefit of this approach is that dispersal distances emerge from the behavioural rules associated with landscape characteristics (Aben et al, 2016).

Choosing a suitable model

To model connections and movement through space effectively consideration needs to be given to which methods are most appropriate for the specific context. The approach adopted will depend on the question set, the behavioural characteristics of the specifics being modelled and, to some extent, data availability. These will determine whether vector or raster analysis is most appropriate and which modelling approach is adopted. They will also influence decisions such as the most appropriate scale and resolution to work at.

The key start point for determining the approach undertaken is the movement or means of connection being modelled. Modelling of traffic, for example, will naturally be restricted to roads which are linear features and therefore well represented in a network model (Delamater et al., 2012). On the other hand measures of landscape connectivity for a given species are likely to require consideration of movement through broader open spaces better respresented by a raster data model (Mulrooney et al., 2017). Related to this is consideration of the format of key data inputs. While choice of modelling approach should not necessarly be determined by the format of data inputs, there is often good fit between appropriate data and modelling approaches. Features such as roads, paths, rail, rivers, ultility pipelines etc are typically represented as linear features easily represented within a network dataset, which are effective for modelling flows of traffic, individuals and good through these linear structures. Meanwhile modelling of movement through open spcaes often requires consideration of factors such as slope or land cover which are most commonly available as raster datasets and well suited to use within raster cost distance calculations and other raster models (Saha et al, 2005).

Regardless of the modelling approach, the scale or resolution of analysis undertaken is key to its effectiveness. The scale of the analysis needs to be appropriate to the phenomenon studied if relevant outputs are to be produced (Wu, 2004). In a vector context smaller-scale data is typically more generalised, which not only influences the shape of linear features but also distances measured (João, 2002). This principle is illustrated clearly in Figure 4. In this example distances measured using the 1:250,000 scale dataset are 17% longer than those measures using the 1:1,000,000 scale data. The inaccuracies in distance measurement will vary not only with scale, but also depending on the features themselves, such as sinuosity of the river.

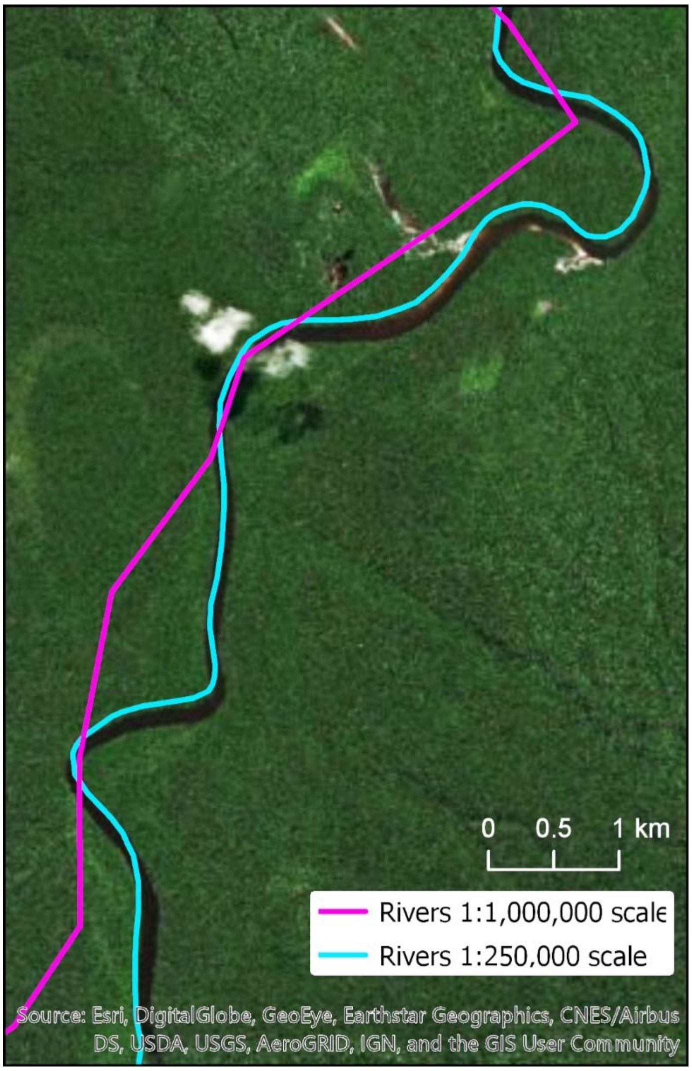

Figure 4: Section of Rio Abacaxis, Brazil, demonstrating the impact of scale on distance measurements. Length of river section at the scale of 1:1,000,000 is 12.8km and at the scale of 1:250,000 is 15.5km

The appropriate resolution for raster analysis is also critical to the accuracy of results gained, as discussed earlier in the review. Within a raster model lower resolution inputs may over generalise routes taken and fail to account for smaller landscape features that may have a significant influence on movement (Atkinson et al., 2005).

The detail and complexity with which attributes are stored also varies considerably between models. While numerous attributes can be selected and combined each time a new network operation is run, each raster model can only represent one set of attributes. Both costs and barriers must be combined into a single cost raster, and each subsequent cost distance surface is specific to one origin. While processing time for one set of origins and destinations may potentially be faster using a raster model (Mulrooney et al., 2017), network models offer the greatest flexibility when comparing multiple combinations of origin or destination, or finding the optimal order to visit a number of locations (Balstrøm, 2002). This is illustrated well through the contrasting modelling approaches I present for examining journey-time exposure to air pollution (Davies & Whyatt, 2009; Davies & Whyatt, 2014).

There are many other factors which may influence the choice of model used. Whether the purpose is to identify a specific route that minimises cost of movement across the landscape, or whether the purpose is to measure connectivity of locations will determine whether it is more appropriate to compute a path or a corridor made from a permeable swath of pixels (Leoniak et al, 2012); or whether to generate least-cost distances or resistance distances (Avon & Berges, 2016).

As already discussed, model results are sensitive to the approach applied, and there is no clear ‘winner’ between different types of model. Ultimately, the user needs to decide which is most appropriate for the characteristics of their study. My published work reflects this, demonstrating the strengths of a variety of different approaches in different contexts.

Conclusions

The repeated challenges that are evident in the literature culminate around the central problem of how we take the complexities of human and animal behaviour and model them in a meaningful way within the constraints of the spatial data models available to us within a GIS. Models of movement require consideration of the geography through which individuals move, individual behavioural state, and interactions with others (Ahearn et al, 2015). The review has highlighted the sensitivity of results to the type of model used, the scale or resolution of data inputs and analysis and the knowledge used to assign values (e.g. speed) to parameters. Care also needs to be applied to consider the potential edge effects around a study area, where accessibility to places located beyond the defined study region may influence results. Even considering these constraints, GIS however remains a powerful tool for understanding connections and movement through space, and for modelling those connections and movements in ways that help further understand issues such as access and exposure, and which may in turn influence behaviour, planning or policy.

For each challenge addressed there remain limitations regarding how effectively we can model reality. Beier et al (2013) sum this up well in the introduction to their CorridorDesigner tool by stating "don't expect to get the truth". Take the raster least-cost modelling of journey-time exposure to air pollution (Davies & Whyatt, 2009). Here we can model traversable space in great detail, ensuring that narrow features like gateways are observed. We may assume that the pollution concentrations modelled are sufficiently representative. With additional work we may then add additional complexity to the cost surface which gives greater preference to walking on tarmac than walking over grass. There will, however, always be other more complex patterns of behaviour that cannot be generalised or easily modelled, for example: the child who fears walking through the park alone but happily walks through it with a parent; the boy who alters his route on wet days because he has a hole in his shoe; or the girl who takes a much longer route so that she can walk with her friend. We can thus model potential for exposure reduction, but we cannot fully model the complexity of human behaviour or predict the likelihood that people will adopt alternative routes proposed.

Despite the challenges of modelling behaviour accurately, the methods I have developed and applied throughout my research each have potential to be adapted and expanded within their specific contexts but also more broadly in the understanding of connections and movement through space. Both the raster and network methods developed to assess journey-time exposure to air pollution could be expanded and used to model the impact of measures put in place to reduce air pollution in specific locations. They could also be used in the planning of cycle routes, using raster least-cost models to identify routes for new custom built cycle paths, or network analysis to identify optimal sections of road which might benefit from cycle lanes designed to prioritise routes which minimise journey-time exposure to air pollution.

The understanding developed to assess the impact of urban lighting on bats could be expanded beyond exploring the land cover types that contribute to habitat connectivity and simple dark or bright city scenarios, to assess the impact of smaller more subtle changes relevant in planning and policy contexts. This may include modelling the impact of policies to reduce the number of street lights switched on overnight in residential areas, or assess the impact of adding or removing trees within a development process.

All analysis is sensitive to the parameters and thresholds that are assigned. This is potentially pertinent in the example of the food desert analysis I undertook within rainforest cities. While field observation and expert opinion were used to determine the thresholds defined, subtle changes in the distance threshold specified, or the selection of products for which access was required, could make significant changes to the extent of the food deserts defined. Even the most accurate parameters will not, however, be able to account for the considerable variation in household behaviours such as different shopping practices or shops on route between destinations e.g. on the way to or from work. Here the analysis taken needs to be considered illustrative and is still useful for assessing the function of networks of small shops for food provision, providing comparisons between neighbourhoods with different poverty levels, and identifying the products that most contribute to the presence of food deserts. The method developed here is not only flexible in its applicability for studying food deserts in other settings, either with or without supermarket penetration, but is also adaptable for studies of service accessibility. Given sufficient data inputs the approach used also has flexibility to potentially incorporate non-retail food sourcing, such as access to public fruit trees.

In exploring the impact of remoteness on vulnerability to climate shocks, one key component that the current network model fails to account for is the impact of climate shocks on the transport network. Both drought and flood events do however impact both road and river transportation. Some roads become impassable during flood events, especially those which are not tarmacked. Meanwhile river navigation during drought becomes problematic in some areas when river levels drop making boat transportation either hazardous or impossible. Modelling the impact of these events on the transport network is complex given the lack of currently available data, but is an area I am exploring further.

Unlike the other published work I have submitted, which modelled connections and movements, my work in North Belfast understanding the impact of segregation on people's everyday mobility focused on monitoring behaviour. Here insufficient information was known about the mobility patterns of the population to be able to model their movement in the first instance. However, having developed a greater understanding of the spaces that people move within during everyday life, there is potential to better model movement through networks using attribution that reflects the probability of movement through different types of group space. With better understanding of mobility patterns, further research could begin to explore inefficiencies in route choice and access to service provision.

Having developed in depth understanding of the ways connections and movement can be modelled and the potential limitations associated with modelling real world behaviour within a GIS, I see not only the opportunities for further usage of these approaches within the fields already discusses, but also the potential to apply these concepts in new areas. For example, the understanding gained over the course of this published work has contributed towards the development of a research proposal which would capture understanding of the use of space within refugee camps. Understanding of movement, and how fear influences this, can then be used to model accessibility of essential services. Better understanding of the use of space and movement within the camps can hopefully, in turn, impact future site design and positively impact the lives of some of the most vulnerable by providing them with greater connections to the space and services they most require.

The body of work here explores the application of existing network and raster least-cost approaches to bring new understanding of movement to a variety of topics, and across vastly different scales. In the midst of specific research questions addressed a number of new approaches and techniques have been developed through this work that could be more broadly applied elsewhere. This includes:

1) The development of a pavement model for walking networks. This could be useful in other contexts for example, modelling routes that minimise crossing of main roads for school children, identifying optimal locations for new crossing points, or modelling accessibility accounting for features such as dropped curbs.

2) Incorporation of directional slope into network models is useful not only for assigning the effort required to traverse the network, but also for assessing accessibility constraints.

3) The approach developed to model network movement through wide rivers (represented originally as polygons) is not only applicable to other riverine contexts, but could also be applied within land-based network datasets where limited areas of open space need to be incorporated into a network data model.

4) Methods developed for the analysis of food deserts, combining cost distance surfaces using map overlay could also be used to incorporate accessibility in many contexts, especially within urban planning.

5) The adaptation of Grannis' T-community concept creates useful definition of neighbourhoods that relate to how space is meaningfully connected. T-communities could therefore be applied not only in the context of the spaces people move within, but also as means of defining neighbourhoods for other social studies.

I am already exploring future applications of the techniques developed, gaps identified and understanding gained through this work to date. For example, I am involved in further work to better understand the transport geography within the Amazon, including the impacts of seasonality and extreme events. The understanding of everyday movement patterns in Belfast has potential to be incorporated into agent based modelling work currently under development for the study area.

Our connections in space, whether to food, services, recreational spaces, or each other influence many aspects of everyday life, for all species. While the real world, and individual behaviours may be too complex to ever model perfectly, this does not mean that there is not significant value and understanding to be gained through what we are able to model. As seen through the critical review, the scale and resolution of analysis are important and need to be suited to the context in question. Results are also sensitive to parameters used and empirical evidence should be used where possible to enhance understanding. Despite the limitations of modelling real world behaviour, the methods available within a GIS context enable enhanced understanding of connections and movement through space in turn may impact planning and policy in the future.

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Submitted publications

[included here are copies of the submitted publications which are open access]

Modelling functional connectivity pathways for bats in urban landscapes

Gemma Davies[1], James Hale[2], Jon Sadler[2]

[1]Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ
Tel. +44 (0)1524 510252
gemma.davies@lancaster.ac.uk
[2]School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT

Summary: With the extent and density of urbanised land-use set to increase, implications arise for the quality of semi-natural and ecological processes. This paper incorporates empirical evidence from a study of gap crossing within a least-cost path methodology to develop a model of functional habitat connectivity for *P. pipistrellus* within the City of Birmingham. The model takes into particular consideration lighting and distance from trees, which are known to influence routes chosen by this species. The landcover types responsible for delivering function connectivity were then analysed, with initial results suggesting greater importance than would be expected for some landcover types such as gardens.

KEYWORDS: bats; least-cost; networks; connectivity; urban ecology

1. Introduction

Movement between resource patches is an important process in the life history of many species. The role of landscape structure in facilitating movement is of particular interest to landscape ecologists (Belisle 2002). However, structurally connected habitats do not necessarily equate to functionally connected habitats. Additional characteristics of the landscape may also influence the degree to which movement between patches is impeded such as the nature of land-cover and land-use types. Translating species specific responses to movement barriers into travel costs may be a particularly effective approach to estimating functional connectivity (Belisle 2005).

The extent of urbanised land-use is set to increase, characterized by an increase in sealed land-cover density (McKinney 2002) and fragmentation of land-use patches (Luck and Wu J 2002; Zhang et al 2004). Green networks and corridors have been influential in guiding city planning in many areas of the world (Fleury and Brown 1997; Turner T 2006). However, there are very few studies that focus on their role in delivering functional connectivity within urban areas and how this varies with the density and composition of the built form. Some bat (Chiroptera) species are sensitive to structural connectivity as well as land-cover types and land-uses, so are ideal model organisms for analyses of this nature.

This paper seeks to analyse functional connectivity for *Pipistrellus pipistrellus* (Schreber 1774), a nocturnal species of insectivorous bat commonly present in urban areas in the UK. Least-cost analysis is a method widely used to analyse habitat connectivity and animal movement (Ganskopp et al. 2000, Halpin and Bunn 2000, Gonzales and Gergel 2007) but often lacks empirical data to inform cost values (Rayfield et al 2010). This paper demonstrates the incorporation of empirical evidence within a least-cost path methodology to develop a model of functional habitat connectivity for *P. pipistrellus* . This species is known to move preferentially along tree lines (Verboom 1997), and is responsive to artificial lighting (Arelttaz 2000). Estimates of distance and lighting thresholds for gap crossing were therefore derived from field surveys, to inform the modelling of a cost surface. The implications for functional connectivity of an urban landscape were subsequently explored through least cost path modelling.

2. Methodology

2.1 Data Inputs

A high-resolution nighttime photographic survey (2008) was secured for the City of Birmingham (UK), resampled to 1m pixel resolution, ground-truthed and reclassified to represent ground incident lux (lx). Vegetation cover was estimated using aerial near-infrared photography (2007) at 2m pixel resolution and was combined with photogrammetric data (2007) to generate a GIS layer representing trees greater than 4m in height. The lighting and tree cover datasets were used to identify gaps in tree lines suitable for bat surveys. 24 survey sites were selected, stratified between three median distance classes (20-40m, 40-60m and 60-80m) and three median lux classes (0lx, 0-20 and 20+). The flight path of each crossing bat were recorded using thermal and infra red cameras and mapped in a GIS (Fig 1). The crossing distance and maximum lux for each flight path were calculated. Bat activity was recorded at each site, but where no crossing events were recorded, the distance and lux for the darkest possible flight path were calculated. Data from the most common bat species *P. pipistrellus* was then used to inform the creation of a cost surface for the study area.

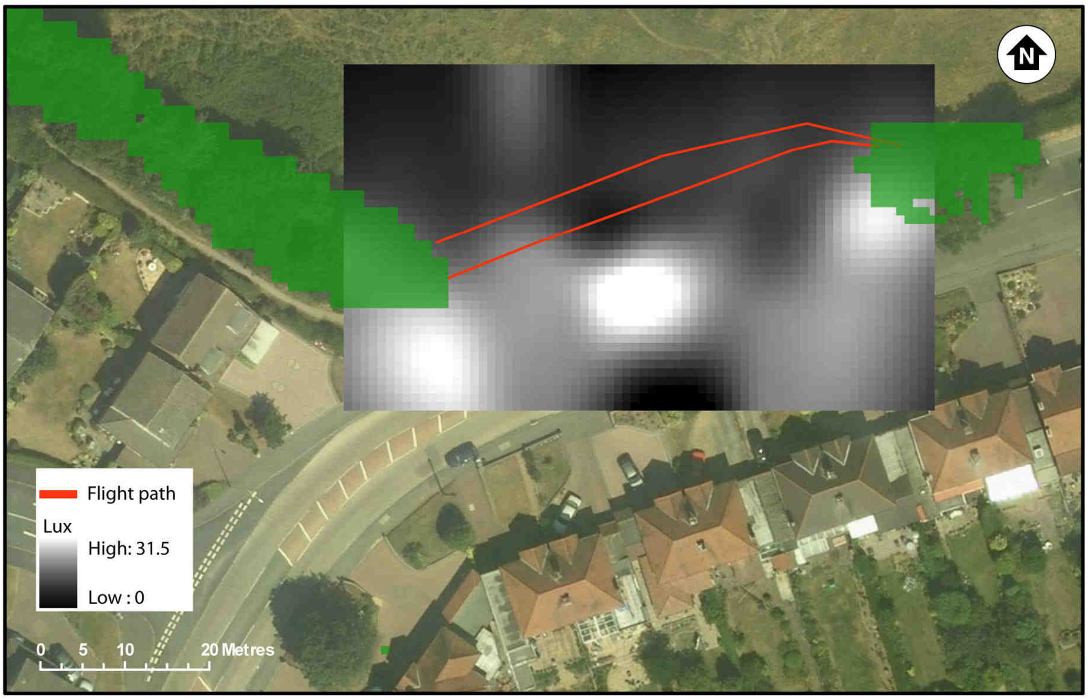

Figure 1: An example of a lit gap in a tree line, overlain with two bat flight paths.

2.2 Creating a cost surface

Using data from the field studies of flight paths, binomial models for gap crossing were developed for both distance from trees (metres) and artificial light (lux). The modelled probabilities of crossing were in turn translated into look-up tables from which distance from trees and light were reclassified into surfaces representing the probability that a bat would move through a given a location. These surfaces were then inverted to convert the probabilities into cost surfaces, then multiplied together to reflect the interaction between distance from trees and light. The final cost surface represents the impedance on bat movement through the landscape.

2.3 Calculating least-cost paths

In order to simulate the movement of our target bat species through the landscape, a series of least-cost paths were developed representing the routes of lowest accumulated cost which bats would in theory be most likely to use. Least-cost surfaces were generated for each of eleven origins, representing a selection of ponds throughout the study area, chosen for similar size and characteristics. Ponds were chosen, given their value as feeding sites for *P pipistrellus* and therefore the importance of their accessibility. A grid of sample points evenly placed at 50m intervals were then specified as the destinations to which least-cost paths would be generated. Only sample points falling within a 500m radius of the associated pond where used as inputs for this stage of the analysis, as this was the maximum spatial scale found to be relevant to explaining *P. pipistrellus* activity on urban ponds (Hale et al. in press).

The least-cost paths were made into a network data set, then using an Origin Destination (OD) cost matrix the length of routes along the least-cost paths to each destination was calculated using ArcGIS Network Analyst. The number of sample points whose least-cost path to the pond was less than 500m was used as an indicator of functional connectivity. This was intended to reflect the proportion of landscape that theoretically has access to each pond, facilitating comparison between different parts of the landscape.

By buffering the least-cost paths from each pond by 10m and extracting the underlying landcover as represented by the Ordnance Survey MasterMap topography layer, an indication of the land cover types responsible for delivering least-cost paths at each site was derived. In addition, for each pond the proportion of land cover within 10m of the paths was compared to the overall landcover within 500m of the pond. This provided an indication of land cover types that were disproportionately responsible for delivering connectivity.

All data processing and analysis was computed using python script with ArcGIS10.

3. Results

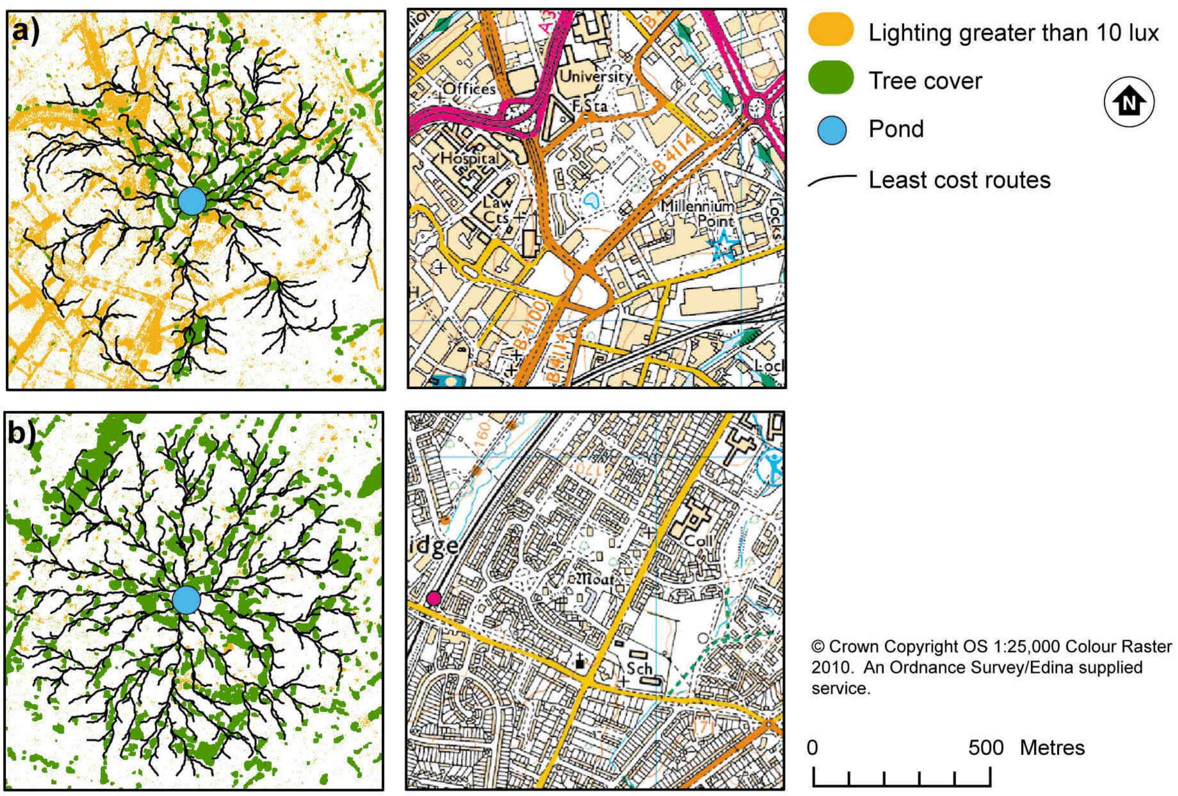

Figure 2: Contrasting least -cost path networks surrounding a) a city centre pond and b) a pond located in a residential suburb

The landscape across the study area varies both in the density of built landcover as well as associated tree cover and lighting levels. These in turn influence the functional capability of the landscape. For example, figure 2 shows the least-cost paths for two of the ponds studied. Pond A is situated in a city centre location with the density of built landcover within 500m at 81%, with a proportion of sample points with least-cost paths to the pond of less than 500m of 58%. Meanwhile Pond B is situated in a residential suburb with a built density of only 39% and with 69% of points reached within 500m. In general, there is a pattern of decreasing landscape connectivity with increasing built density. 40% of least cost routes pass through the built form (man-made surfaces), while of the remaining landcover types, gardens account for 31% of routes and semi-natural green spaces account for 24%. These figures, however, fail to account for the proportions of overall landcover available. The next step was, therefore, to take into consideration the difference between the proportion of land cover responsible for delivering the least-cost paths and the overall proportion of that land cover type available. Figure 3 shows that gardens appear to deliver a greater proportion of least-cost paths than would be expected if all landcover was favoured equally. Meanwhile roads and other built surfaces are less favoured. The variation between sites appears to be due to the surrounding built density, with gardens delivering a disproportionately high level of connectivity in low density areas.

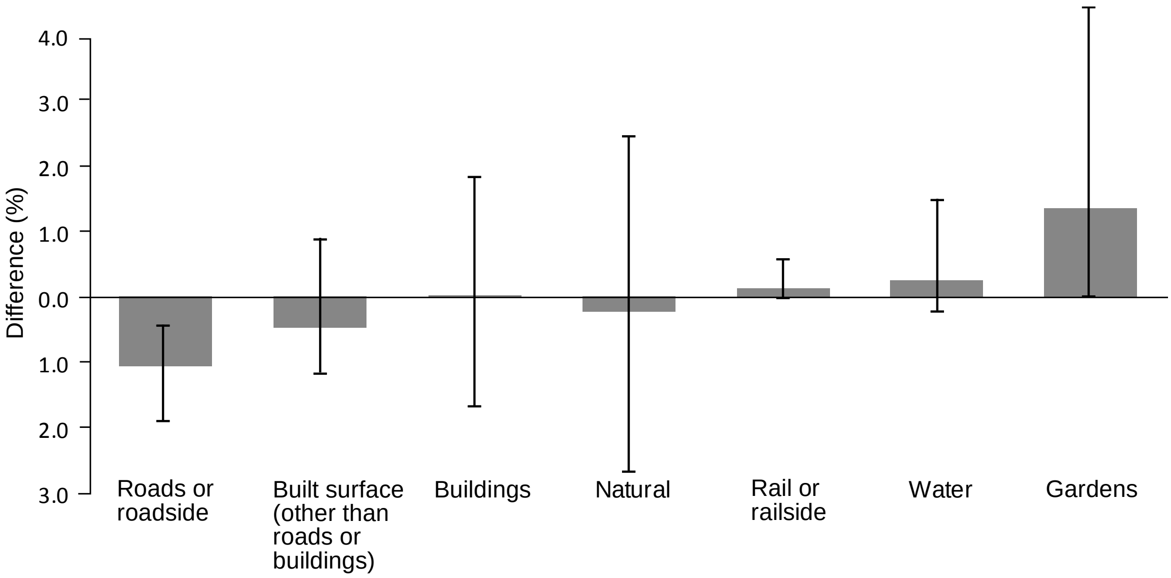

Figure 3: Difference between landcover delivering least-cost paths and entire landcover available within 500m of ponds

4. Discussion

The initial results presented suggest greater importance for some landcover types such as gardens than would be expected, in delivering connectivity. That modelled functional landscape connectivity for *P. pipistrellus* appears to reduce with built density has implications for housing density targets and urban biodiversity policy. The results are potentially sensitive to the way in which the empirical evidence is interpreted and input into the model and further work is, therefore, also required to test the sensitivity of the model to these inputs. In addition, the spectral quality of the lighting and composition of the tree lines may also be significant and should be explored further.

One limitation is that the model assumes all individuals within a population have the same ability and motivation to disperse and that they incur the same movement costs. This may not be the case (Belisle 2005) and models may be further refined to reflect this. A second limitation is that our model assumes individuals are dispersed evenly over the landscape and are all trying to move towards a central point (pond). In reality, roosts will not be spread evenly and bats may move between several ponds and other feeding areas. Therefore, future work might also consider modelling connectivity between potential roost locations and multiple feeding destinations and comparing bat activity of routes with differing modelled costs.

5. Acknowledgements

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7. Biography

Gemma Davies is the GIS Officer for Lancaster Environment Centre.

James Hale is an urban ecologist at the University of Birmingham, with a particular interest in measuring functional landscape connectivity.

Dr Jon Sadler is a reader in Biogeography at the University of Birmingham. With principal research interests in the community/population dynamics of urban and riparian areas.

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The ecological impact of city lighting scenarios: exploring gap crossing thresholds for urban bats

JAMES D. HALE[1], ALISON J. FAIRBRASS[2], THOMAS J. MATTHEWS[3,4], GEMMA DAVIES[5] and JON P. SADLER[1]

[1]*School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK,* [2]*Centre for Urban Sustainability and Resilience, University College London, Chadwick Building, Gower Street, London WC1E 6BT, UK,* [3]*School of Geography and the Environment, Oxford University Centre for the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK,* [4]*CE3C – Centre for Ecology, Evolution and Environmental Changes/Azorean Biodiversity Group and Universidade dos Açores, Departamento de Ciências Agrárias, Portugal,* [5]*Lancaster Environment Centre, Lancaster University, Lancaster LA1 4QY, UK*

Abstract

As the global population urbanizes, dramatic changes are expected in city lighting and the urban form, which may threaten the functioning of urban ecosystems and the services they deliver. However, little is known about the ecological impact of lighting in different urban contexts. Movement is an important ecological process that can be disrupted by artificial lighting. We explored the impact of lighting on gap crossing for *Pipistrellus pipistrellus*, a species of bat (Chiroptera) common within UK cities. We aimed to determine whether the probability of crossing gaps in tree cover varied with crossing distance and lighting level, through stratified field surveys. We then used the resulting data on barrier thresholds to model the landscape resistance due to lighting across an entire city and explored the potential impact of scenarios for future changes to street lighting. The level of illumination required to create a barrier effect reduced as crossing distance increased. For those gaps where crossing was recorded, bats selected the darker parts of gaps. Heavily built parts of the case study city were associated with large and brightly lit gaps, and spatial models indicate movement would be highly restricted in these areas. Under a scenario for brighter street lighting, the area of accessible land cover was further reduced in heavily built parts of the city. We believe that this is the first study to demonstrate how lighting may create resistance to species movement throughout an entire city. That connectivity in urban areas is being disrupted for a relatively common species raises questions about the impacts on less tolerant groups and the resilience of bat communities in urban centres. However, this mechanistic approach raises the possibility that some ecological function could be restored in these areas through the strategic dimming of lighting and narrowing of gaps.

Keywords: connectivity, gap crossing, lighting, movement, *Pipistrellus pipistrellus*, scenarios, urban, urbanization

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Introduction

Urban areas are now home to over half of the world's population (UN, 2010), are the drivers behind much of the global CO_2 emissions and resource demands (Wackernagel *et al.*, 2006; Hoornweg *et al.*, 2011) and are highly modified environments (Grimm *et al.*, 2008). They are therefore at the heart of debates about climate change, resource security, nature conservation, and human well-being (Newman, 2006; Grimm *et al.*, 2008; Hodson & Marvin, 2009; Glaeser, 2011). Given the diversity and complexity of change within urban areas (Dallimer *et al.*, 2011), there is a need to explore how their sustainability performance might vary under alternative scenarios for their future structure and operation (Lombardi *et al.*, 2012). In this study, we explore how the disruption of the nocturnal urban environment by different levels of artificial lighting can impact species movement – a key ecological process.

Growth, sprawl, compaction, and fragmentation of the built form varies within and between urban areas (Williams, 1999; Luck & Wu, 2002; Couch *et al.*, 2005; Irwin & Bockstael, 2007; Adams *et al.*, 2010; Seto *et al.*, 2011), and changes in built extent, density, and land use may occur over relatively short time periods (Pauleit *et al.*, 2005; Seto & Fragkias, 2005; Dallimer *et al.*, 2011). In addition to shifts in urban form, changing technologies and social practices also radically alter urban environments (Gandy, 2004). One important example is outdoor artificial lighting, a pervasive yet diverse characteristic of cities that is changing in many

Correspondence: James D. Hale, tel. 07724381144, fax +44 (0)121 41 45528, e-mail: j.hale@bham.ac.uk; Jon P. Sadler, tel. +44 (0)121 41 45776, fax +44 (0)121 41 45528, e-mail: j.p.sadler@bham.ac.uk

regions (Bennie *et al.*, 2014a; Kyba *et al.*, 2014). Remotely sensed measures of light emissions from the earth's surface have been found to correlate with built land cover (Hale *et al.*, 2013), population density (Sutton *et al.*, 1997), electric power consumption (Elvidge *et al.*, 1997), and per capita income (Ebener *et al.*, 2005). Outdoor artificial lighting also varies considerably within cities depending on land cover and land use (Luginbuhl *et al.*, 2009; Kuechly *et al.*, 2012; Hale *et al.*, 2013; Levin *et al.*, 2014). Intensification and expansion of lighting is evident at both local and global scales (Hölker *et al.*, 2010a; Bennie *et al.*, 2014a), a process fuelled by the emergence of cheaper and more efficient lighting technologies (Tsao *et al.*, 2010; Kyba *et al.*, 2014). The large-scale introduction of such technologies would also be expected to result in changes to the dominant spectral composition of outdoor lighting (Stone *et al.*, 2012). However, despite a broad trend of growth in artificial lighting, some locations are becoming darker (Bennie *et al.*, 2014a) as lamps are shielded, dimmed, or even removed to reduce light pollution, running costs, and carbon emissions (RCEP, 2009; Falchi *et al.*, 2011; Gaston *et al.*, 2012). Changes in artificial lighting can impact city performance in a variety of ways (Smith, 2009; Falchi *et al.*, 2011), yet many of the potential sustainability impacts remain unexplored (Hölker *et al.*, 2010a; Lyytimaki *et al.*, 2012). The nature of lighting infrastructure and its operation has obvious implications for energy demands and costs (Gallaway *et al.*, 2010; Tsao *et al.*, 2010). However, artificial lighting also has numerous positive and negative impacts on social practices and human health; lighting has enabled greater flexibility in the timing of work and leisure activities, although at the cost of disruption to circadian rhythms, behaviours, and physiological processes (e.g. Navara & Nelson, 2007; Falchi *et al.*, 2011; Cho *et al.*, 2013). Less is known, however, about how natural systems are disturbed and the resulting effects on ecological function and service provision (Rich & Longcore, 2006; Hölker *et al.*, 2010b; Gaston *et al.*, 2012).

In this study, we focus on ecological impacts of artificial lighting in urban areas and explore how these may vary with different levels of illumination and configurations of the built form.

The value of the semi-natural components of cities is increasingly recognized, particularly from the perspective of those ecosystem functions with strong links to human well-being (Carpenter *et al.*, 2006; Sadler *et al.*, 2010; Haase *et al.*, 2014). Given the known effects of artificial lighting on a variety of species and habitats (Longcore & Rich, 2004; Hölker *et al.*, 2010b; Gaston *et al.*, 2012) and the rapid changes to urban street lighting already underway, research is needed that explores the potential disruption of ecological processes at the city scale. Individuals of most species are sensitive to natural cycles of day and night (Hölker *et al.*, 2010b), with light acting both as information and a resource (Gaston *et al.*, 2013). For some species, the disruption of these cycles by artificial lighting can impair particular parts of their life history, for example feeding and growth (Boldogh *et al.*, 2007), commuting to foraging sites (Stone *et al.*, 2009) or the timing of reproduction (Kempenaers *et al.*, 2010). Conversely, lighting can bring direct advantages such as concentrating prey (Blake *et al.*, 1994; Jung & Kalko, 2010) or for diurnal and crepuscular species, it may extend the hours of activity (Negro *et al.*, 2000). A further complication is that lighting may deliver both costs and benefits to a single individual, making the net impact challenging to estimate. For example, artificial lighting has been found to delay roost emergence in the bat *Pipistrellus pygmaeus* (Downs *et al.*, 2003), but also to provide foraging locations for the same species (Bartonička *et al.*, 2008). Impacts on individual fitness may be sufficient to alter populations and even community composition (Perkin *et al.*, 2011; Davies *et al.*, 2012), with the potential to affect important ecosystem functions and services such as pollination (Eisenbeis, 2006) or seed dispersal (Lewanzik & Voigt, 2014). However, population or ecosystem-scale research related to artificial lighting is rare (Gaston *et al.*, 2013; Lyytimäki, 2013). One further notable research gap relates to lighting thresholds for ecological impacts and their spatial extent (Gaston *et al.*, 2013).

Here, we examine the impact of lighting on animal movement within urban areas as movement is a process relevant to individual fitness, to population resilience and to broader ecosystem structure and function (Nathan *et al.*, 2008). Despite the importance of movement for enabling organisms to forage, disperse, and ensure gene flow between populations, the direct measurement of functional connectivity is not always practical (Nathan *et al.*, 2008; Zeller *et al.*, 2012). Tracking and genetic studies may provide evidence that some patches within a landscape are functionally connected, but on their own, these approaches fail to explain why movement may have been recorded in some contexts but not in others. Understanding the factors that affect movement between habitat patches is therefore important for conservation practice (Rayfield *et al.*, 2010; Watts *et al.*, 2010), particularly in landscapes undergoing rapid environmental change (Zeller *et al.*, 2012). This can be highly complicated as movement may not only depend on patterns of land cover and land use within a landscape, but also on the motivation and ability of individuals to move (Tischendorf & Fahrig, 2000; Nathan *et al.*, 2008; Pe'er *et al.*, 2011).

The flight behaviour of several bat species may be influenced by artificial lighting (Kuijper *et al.*, 2008; Stone *et al.*, 2009, 2012; Polak *et al.*, 2011) which can cause deviation of the flight path to avoid the most heavily lit area (Kuijper *et al.*, 2008; Stone *et al.*, 2009), or barrier effects where approaching bats turn and fly in the opposite direction (Stone *et al.*, 2009). Barrier effects on commuting bats have also been demonstrated for structures such as motorways that bisect habitat networks (Kerth & Melber, 2009). Several European bat species are known to fly along woodland edges and tree lines when commuting between their roost and feeding locations (Racey & Entwistle, 2003), and the activity of some species is higher with increasing proximity to these corridor features (Verboom & Spoelstra, 1999; Downs & Racey, 2006). This suggests that movement for nocturnal bat species might be simultaneously impacted by the structural fragmentation of habitat networks and by the artificial lighting of commuting routes, both of which are common within urban areas, potentially increasing levels of landscape resistance.

Here, we modelled the effect of both crossing distance and illumination level on the crossing behaviour of a common urban bat (*Pipistrellus pipistrellus*) at gaps in urban tree networks. The resulting model was then used to explore the landscape-scale implications of different urban lighting scenarios for movement.

The study objectives were to:

1. determine whether the probability of bats crossing gaps in tree lines varies with crossing distance and illumination, and to model any barrier effects;
2. develop spatial models for landscape resistance due to artificial lighting; and
3. explore the implications of these resistance models for habitat accessibility along an urban gradient.

Materials and methods

These methods are divided into five distinct sections (Fig. 1): (1) the selection of survey gaps within networks of urban tree cover, (2) surveys of gap crossing events by bats, (3) the development of statistical models for gap crossing probability that identify distance-dependant lighting thresholds for barriers to movement, (4) the translation of this barrier lux model into spatial GIS models for landscape resistance under contrasting lighting scenarios for a case study city, and (5) an analysis of how these scenarios for landscape resistance may impact habitat accessibility along an urban gradient.

Selection of survey gaps

For *P. pipistrellus*, movement between resource patches is facilitated by linear features such as tree lines (Verboom & Spoelstra, 1999) and therefore, the patch-matrix-corridor model (Forman, 1995) would appear to be an appropriate starting point for exploring some of the mechanisms that deliver functional connectivity for this species. A key assumption within this model is that the matrix creates resistance to the movement of individuals between habitat patches and that this resistance is reduced by the presence of linear habitat features that form structural connections between patches. To directly measure functional connectivity between bat roosts and feeding areas within an urban area would be extremely challenging, particularly as both feeding areas and roosts may be difficult to identify or gain access to, given their frequent association with private built infrastructure (Blake *et al.*, 1994; Altringham, 2003). This therefore led us to focus on corridor features known to facilitate movement and to explore the degree to which structural gaps in these features and lighting within the intervening matrix could influence crossing behaviour.

Field observations were undertaken in the summer of 2010 within the West Midlands of the United Kingdom (UK), a highly urbanized metropolitan county covering 902 km^2 with a population of ~2.3 million (S1). *P. pipistrellus* is a species of bat that is broadly distributed over Europe and the Near East (Altringham, 2003), is commonly found within UK cities and can be found throughout the UK West Midlands (Hale *et al.*, 2012). It is nocturnal and easily surveyed and was therefore chosen as a model species for exploring the impacts of lighting on bat movement in urban areas. Bats were surveyed at gaps in networks of tree cover, as this species is known to follow the edges of tree lines when commuting between roosts and feeding areas (Downs & Racey, 2006). Tree cover is ubiquitous within the West Midlands, with the exception of the most densely built areas. Trees are typically located along road edges, railway embankments and waterways, in gardens and recreational green spaces, and within the broader amenity planting of commercial areas. Such trees are rarely isolated, but tend to form linear features that follow existing or historic land use boundaries such as the perimeter of a park or residential development. These lines of trees are readily identifiable from aerial photography, and their canopy typically forms a structural network that connects a variety of urban land covers. Despite this high structural connectivity, gaps within this network are evident. Tree lines were selected that were at least 20 m wide and composed of trees >4 m in height, which we consider ideal commuting features for *P. pipistrellus* (c.f. Verboom & Spoelstra, 1999). Gaps in tree lines were defined as locations where a tree line terminated, but where after a break of at least 20 m, a second tree line continued along approximately the same direction. In some cases, it is likely that such tree lines had originally formed a single boundary feature, which was subsequently bisected by the building of a road. Gaps were illuminated to varying levels (S1) by sodium-vapour street lamps [the dominant source of outdoor artificial lighting within the city (Hale *et al.*, 2013)].

Our aim was to explore the impact of different gap widths and lighting conditions on crossing behaviour. Rather than experimentally manipulating gap characteristics, we identified a selection of gaps within which to undertake surveys, stratified by width and illumination level. To support this stratifica-

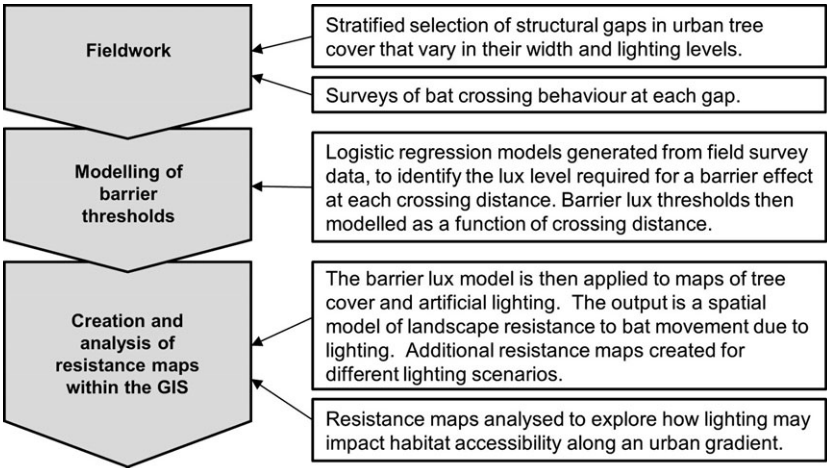

Fig. 1 A flow diagram representing key steps within the methods.

tion process, gaps were each assigned single values for width and illumination as follows: (1) a variety of gaps in tree lines were identified in ArcGIS 9.2 (ESRI, Redlands, CA, USA) using a raster layer representing tree cover >4 m in height derived from remotely sensed 1 m resolution colour and near-infrared photography (2007) (Bluesky International Limited, Coalville, Leicestershire, UK) and LiDAR data (2006) (The GeoInformation Group, Linton, Cambridge, UK). Gaps where the built land cover within a 350 m radius exceeded 60% were excluded, as activity for *P. pipistrellus* tends to be lower in these areas (Hale *et al*., 2012). (2) Measurements of surface illumination within each gap were collected in the field following a 2-m interval grid of survey points, using a USB2000+RAD spectroradiometer (Ocean Optics, Dunedin, FL, USA). (3) These point measurements were subsequently digitized within the GIS, and spline interpolation was used to generate a 1-m resolution raster layer representing surface lux within each gap (Fig. 2). (4) Five transect lines crossing each gap were created in the GIS at 5-m intervals parallel to the main axis of the tree line (Fig. 2), and the length of each transect line was recorded. (5) Each transect line was then intersected with the lux raster to identify the maximum lux encountered, using Hawth's Analysis Tools (Beyer 2004). The result of this process was the calculation of five width and five lux values for each gap (S1). From these, the median width and median lux value were used to characterize each gap, in order to provide typical values to inform the final stratified selection of survey gaps. (6) 27 survey gaps were then chosen to ensure strong coverage across three width and three illumination categories (S1).

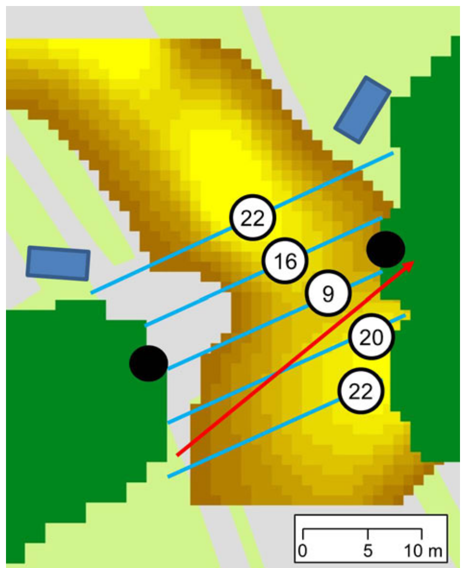

Fig. 2 A gap in an urban tree line caused by a road, as represented in the GIS. Dark green areas represent tree cover >4 m high, and the variation in road surface lux is indicated by the yellow gradient. Parallel transects (blue lines) were used to provide an indication of potential crossing routes, the distance of these routes, and the maximum lux that they encounter (indicated by numbered circles). Actual bat crossing routes (red arrow) were mapped based on surveyor (black circle) observations and confirmed based on camera (blue rectangle) recordings.

Gap crossing surveys

To record crossing behaviour of *P. pipistrellus*, surveys were undertaken at each gap for a 1.5-h period following dusk (c.f. Berthinussen & Altringham, 2012). Surveyors were positioned at either end of the gap and used Batbox Duet detectors (Batbox Ltd., Steyning, West Sussex, UK) to be alerted to approaching bats. As directionality of bat detectors is generally poor, it was necessary for surveyors to identify and record the crossing route of each bat, which was later digitized onto the GIS. This species typically commutes at a height of 2.5–10 m (Russ, 1999; Verboom & Spoelstra, 1999; Berthinussen & Altringham, 2012), and individuals were visible when crossing lit gaps. However, when bats crossed in groups or when dark gaps were surveyed, the crossing routes were confirmed using video recordings. Two cameras were used: a Thermovi-

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sion A20M thermal camera (FLIR Systems, Boston, MA, USA) and a DCR-HC19E digital video camera (Sony Corporation, Kōnan Minato, Tokyo, Japan) in NightShot mode, with additional near-infrared (NIR) lighting provided by a 70° angle 850 nm IR LED flood lamp (Camsecure, Bristol, UK). Such lighting is routinely used in bat surveys (Berthinussen & Altringham, 2012), and we found no research to indicate NIR sensitivity for any bat species. The potential for mammals to sense NIR wavelengths has been raised by Newbold & King (2009) and the possibility of NIR lighting impacting bat behaviour should therefore not be excluded, although we emphasize that our research design was systematic across all sites. Bat calls were recorded using a pair of AnaBat SD1 frequency division bat detectors (Titley Scientific, Lawnton, Queensland, Australia) positioned at either end of the gap, allowing each crossing event to be attributed to a species or species group. Calls were identified in AnalookW (Corben, 2009) using bespoke filters (Hale *et al.*, 2012).

Models for crossing behaviour

Two analyses were undertaken to explore the response of bats to potential crossing routes that differed in their width and illumination level, using data from the gap crossing surveys. The primary analysis sought to identify barrier thresholds for gap crossing, using logistic regression to estimate the probability of a barrier effect (c.f. Awade *et al.*, 2012). First, we created a single data set of distance and lux values (referred to as the 'crossing distance' and 'crossing lux', respectively) for crossing events and failures. For crossing events, these values were extracted from the GIS using the digitized crossing routes. For survey gaps where no crossings were recorded, distance and lux data were extracted from the GIS using the gap transect lines. As lux levels could be highly variable within a gap, we extracted the maximum lux value encountered along each crossing route or gap transect. These data were then used to generate a series of binary logistic regression models in R 2.11.1 (R Core Team, 2014) as follows, using the MASS library (Venables & Ripley, 2002). To explore whether the level of illumination required for a barrier effect (the 'barrier lux') varied with crossing distance, subsets of data were selected for modelling using a 20-m moving window (see Fig. 3 for examples). The barrier lux was defined as the lux level required for a crossing probability of 5% or less. The barrier lux and mid-range distance from each logistic regression model were then used to model barrier lux as a linear function of crossing distance (henceforth referred to as the 'barrier lux model') (Fig. 4).

The second analysis aimed to explore whether the routes taken by bats crossing survey gaps differed from the typical values for the corresponding gaps, in terms of lighting and distance. To highlight potential biases in crossing behaviour, values for the distance of each digitized crossing route were plotted against the median width of the gap being crossed, calculated using distance data from the 5 gap transects. Similarly, the lux of each crossing route was plotted against the median lux value of the gap being crossed.

Spatial models for the impact of artificial lighting on landscape resistance

Generating resistance surfaces is an increasingly popular way to provide quantitative estimates of how different environmental parameters such as land cover type or human population density may impede animal movement (Zeller *et al.*, 2012). Spatial environmental data are typically combined with biological data from surveys to generate cost surfaces that can be interpreted as maps of resistance/barriers to movement. In this case, we created a resistance surface to represent the combined effect of distance from tree cover and illumination by artificial lighting on bat movement. We generated this resistance surface for the city of Birmingham, as it is within the broader West Midlands metropolitan county where our gap surveys were undertaken, and high-resolution lighting and tree cover data are available for the full extent of the city (Hale *et al.*, 2012, 2013). Our aim was to use the barrier lux model to generate a resistance surface using rasters representing distance to tree cover and incident lux as input values for the model variables, from which we could classify the landscape into either accessible or inaccessible patches of land cover. A key assumption within this model was that lighting would have no barrier effect on individuals of *P. pipistrellus* commuting along contiguous tree

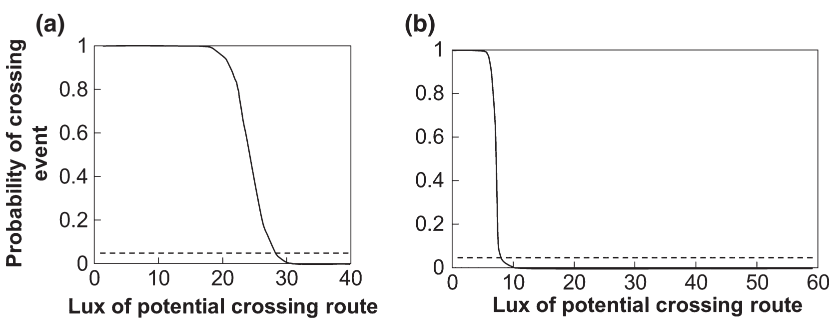

Fig. 3 Examples of binary logistic regression models for the probability of gap crossing by *Pipistrellus pipistrellus* at different lux levels. Models are given for crossing distances of (a) 20–40 m and (b) 60–80 m. The dashed lines indicates where the probability of crossing = 0.05.

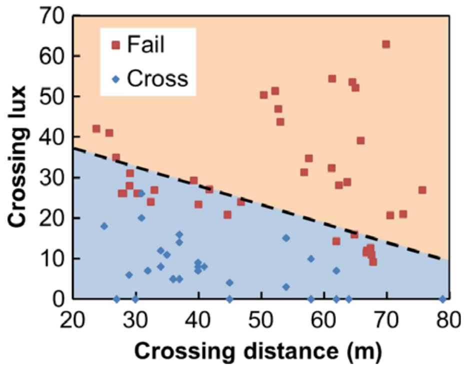

Fig. 4 Gap crossing successes and failures for *Pipistrellus pipistrellus*. For crossing events, the distance and maximum lux for each crossing route are plotted (blue diamonds). For gaps where no crossing events were recorded, the distance and maximum lux for gap transects are plotted (red squares). The dashed line represents an estimate of the barrier lux for any given crossing distance, generated using the linear regression equation from the barrier lux model.

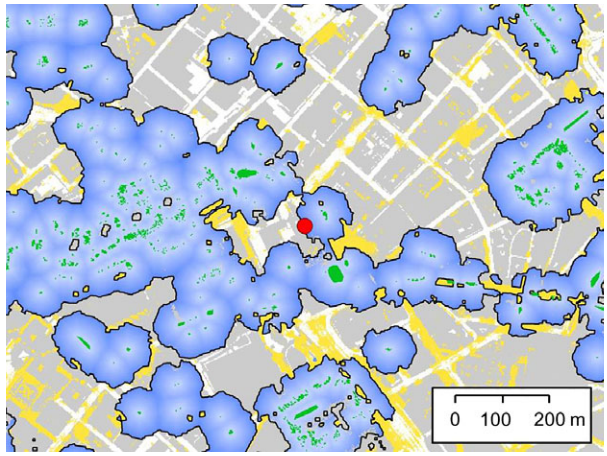

Fig. 5 Zones surrounding urban tree cover where the lighting levels are predicted to be insufficient to act as a barrier to movement for *Pipistrellus pipistrellus*. This was derived from a resistance surface generated within the GIS at 1 m resolution, by applying the barrier lux model to a raster representing distance to tree cover (2006/7) and by comparing the output to a map of incident lux (2009). Key: green = trees >4 m, blue network = areas surrounding tree cover where lighting has no barrier effect, blue gradient indicates distance from tree cover, yellow = surface illuminance >20 lx, grey = buildings, and red dot = an urban pond used by bats for foraging. Building outlines derived from OS MasterMap land cover and land use parcels reprinted from original mapping with permission from the Ordnance Survey (2008).

lines and woodland edges (c.f. Stone *et al*., 2012), but that lighting had the potential to act as a barrier to the crossing of open areas between tree cover.

First, the ArcGIS Cost Distance tool was used to generate a 1-m resolution raster layer for the entire city representing distance to the nearest tree cover >4 m high. In most cases, the output raster values represented linear distance to tree cover. However, nonlinear distance calculations were also permitted to recognize that euclidian distance measures would be inappropriate for locations where tall buildings would create a barrier to straight line flight at typical commuting height. To achieve this, parts of buildings >30 m in height were selected from the 2008 Ordnance Survey MasterMap (OSMM) land use data set and saved as NoData values within a 1-m resolution raster layer. All other raster cells were assigned a value of 1, and this layer was then used as an input cost raster as part of the cost distance calculations. Next, the distance value attributed to each pixel was doubled to represent the minimal possible flight distance for a bat leaving and returning to tree cover via that pixel location. This distance layer was then used to calculate the lux level that would be required for a barrier effect at each pixel location, using the Raster Calculator tool to apply the regression equation from the barrier lux model to the distance value of each pixel value. The resulting barrier lux layer was compared to a second layer representing incident lux (2009) for the entire city at 1 m resolution, estimated from aerial night photography (Hale *et al*., 2013). When the lux value for a pixel from the 2009 lighting data set was equal to or greater than the corresponding pixel value within the barrier lux layer, the pixel was classified as inaccessible to our study species. The resulting resistance surface was converted to a polygon layer representing zones surrounding urban tree cover that would be expected to be accessible to bats, based upon the lighting levels in 2009 (Fig. 5). This process was repeated to generate resistance surfaces for two contrasting urban lighting scenarios. The first scenario was for a city without any lighting (the Dark City) and was intended to serve as a baseline model for the independent effect of the structural connectivity of tree cover on landscape resistance. The second was for a heavily lit scenario (the Bright City). This Bright City scenario used the 2009 lighting layer as a starting point, but the surface lighting values of all roads were increased to a minimum of 20 lux, representing a plausible but extreme scenario for future urban road lighting.

Habitat accessibility along an urban gradient

Urban gradient analyses have been extensively used as a means for exploring the impact of 'intensification' on species presence or abundance. Such approaches are a practical response to concerns about the increasing density and extent of urban areas; yet as many ecologically relevant variables covary along such gradients (Hahs & Mcdonnell, 2006), it is rarely clear how these variables combine to drive the ecological patterns observed. The aim of this analysis was to use GIS analyses to explore how the landscape resistance resulting from variations in urban tree cover and lighting could impact habitat accessibility along a gradient of built land cover. Sampling was centred on small ponds (maximum area 2000 m^2), as these are potential foraging sites for *P. pipistrellus* and are distributed throughout the city. The underlying assumption of this analysis was that ponds would have greater value as foraging habitats if the surrounding landscape had low resistance to bat movement. All ponds within Birmingham were identified from OSMM land use polygons using the GIS and each pond centre was buffered by 350 m, a key spatial scale for predictive models of *P. pipistrellus* activity identified in an earlier study (Hale *et al.*, 2012). The percentage built land cover within 350 m of each pond was then estimated using OSMM polygon data, and each pond was assigned to one of seven 'density classes' ranging from a low density class of 10–20% built land cover, to a class of ponds surrounded by between 70% and 80% built land cover. Thirty-five of these ponds were then selected for use in the gradient analysis, 5 from each density class. A greater number of ponds could not be selected without causing uneven sampling, because few ponds were present in heavily built areas.

The polygon layer representing patches of land cover predicted to be accessible under 2009 lighting levels was then clipped by a 350-m buffer zone surrounding each pond, and those patches that intersected the pond were retained (Fig. 6). The total area of accessible land cover connected to each pond was then recorded as a percentage of the total surface area within 350 m of the pond. This was modelled against the percentage built land cover within the 350-m buffer zone using a generalized additive model (GAM) in R 2.11.1, using the MGCV library (Wood, 2006). This process was then repeated for the accessible land cover models generated for the Dark City and Bright City scenarios.

Results

Crossing behaviour

The majority of the bats that were recorded crossing gaps were *P. pipistrellus*, and therefore, all results presented here relate to this species. Individuals of *P. pipistrellus* were recorded in the vicinity of all survey gaps, but were only observed crossing 19 of the 27 gaps. The lighting threshold for a barrier effect reduced with increasing crossing distance (Fig. 4), following the linear model: barrier lux = −0.46*crossing distance + 46.2, where the barrier lux is the lux value at which the probability of crossing is 5%. The majority of bats (95.6%) selected crossing routes that were darker than the median gap lux value (Fig. 7a), indicating that bats were choosing to cross in the darker parts of gaps, whereas the length of crossing routes was not consistently larger or smaller than the median gap width (Fig. 7b).

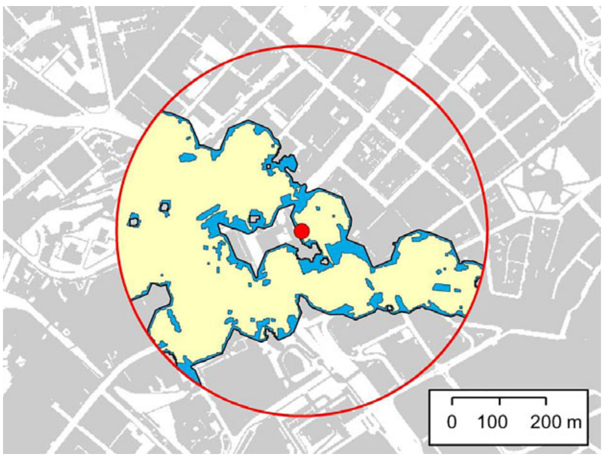

Fig. 6 Two spatial models for areas of accessible land cover within 350 m (red circle) of an urban pond (red dot), under a Dark City scenario (blue) and a Bright City scenario (yellow). In this example, when no lighting is present, 44% of the local landscape is predicted to be accessible from the pond, shrinking to 36% in the brightly lit scenario.

Landscape connectivity analysis

Landscape resistance for *P. pipistrellus* varied within the City of Birmingham (Fig. 8a) along a gradient of built density (Fig. 8b), as a result of the fine grained arrangement of trees and lighting (S2). When modelled using 2009 lighting data, accessible land cover was highest in areas where built surfaces account for <25% of the landscape, but dropped markedly when built land cover was >65%. Much of this effect is due to the abundance and arrangement of tree cover, although the impact of lighting is clear at higher built densities (Fig. 9). Compared to a Dark City model, lighting levels in 2009 further reduce the percentage of accessible land cover surrounding ponds by up to 5% in heavily built areas, and by up to 7% under a Bright City scenario (Fig. 9).

Discussion

Outdoor artificial lighting is one of many urban characteristics that are changing rapidly across the globe, yet relatively little is known about its unintended consequences for environmental well-being. There is a need for research to identify these potential impacts and to contextualize the results in a way that allows mitigation to be targeted effectively. Our analysis demonstrates that lighting can affect landscape resistance in cities, even for a species of bat (*P. pipistrellus*) that that has been recorded in many urban land cover types (Gaisler *et al.*, 1998; Hale *et al.*, 2012). The greatest impacts on this species are likely to be in brightly lit areas where structural connectivity of tree cover is already low, characteristics typical of heavily built areas such as urban centres.

Bats, connectivity, and lighting

There is a need to better understand those factors that influence the ability of organisms to move between resource patches and for tools that can predict the impacts of changes at a landscape scale (Adriaensen

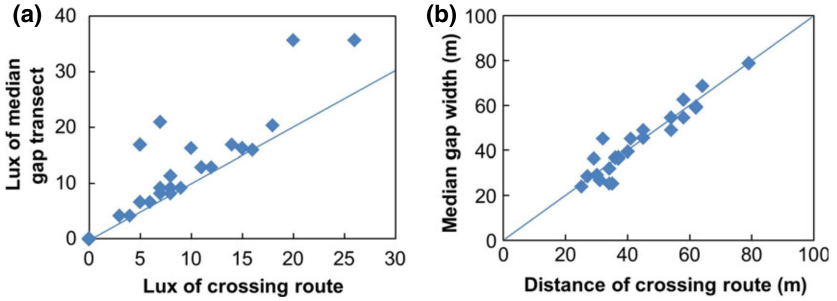

Fig. 7 (a) Maximum lux for bat crossing routes vs. maximum lux of the median gap transect. The line indicates where the crossing route lux and gap lux values are equal. (b) Distance of each crossing route vs. the median gap width (based upon gap transects). The line indicates where the crossing route distance and gap width are equal.

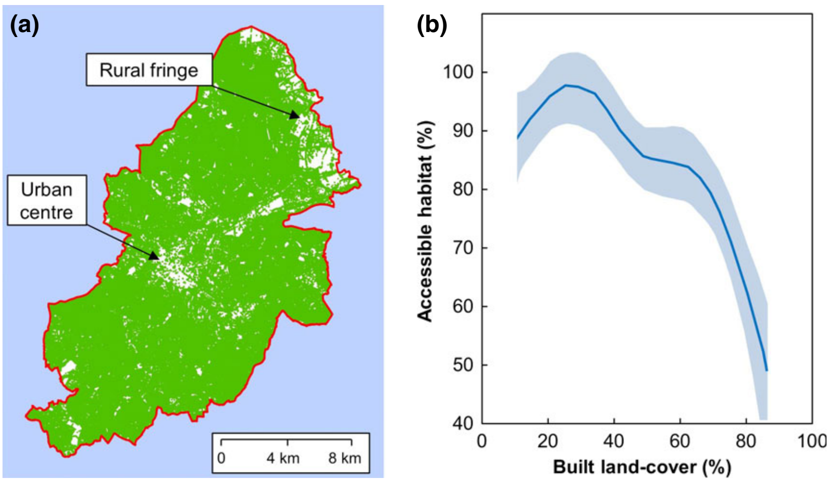

Fig. 8 (a) A spatial model of areas within the City of Birmingham where accessibility for *Pipistrellus pipistrellus* is not restricted (indicated by green networks) by artificial lighting levels present in 2009. Accessible land cover is poor in the urban centre and other highly built up areas, as well as at the rural fringe. (b) Estimates of habitat accessibility along a gradient of built surface cover, based on measurements for 35 typical 'foraging ponds'. Habitat accessibility is defined as the percentage of surface area within a 350 m radius of each pond that the model predicts to be available to bats under a given lighting scenario and that also intersects the pond. Shaded areas represent 95% confidence intervals.

et al., 2003). Central to this is the recognition that functional connectivity of habitats is dependent on both landscape structure and individual behaviour (Tischendorf & Fahrig, 2000). To our knowledge, this is the first study to quantify the effect of lighting on gap crossing in bats and to explore how barrier effects may accumulate across a landscape. Distance thresholds for gap crossing have been identified in the field for groups such as birds (Creegan & Osborne, 2005; Awade & Metzger, 2008) and mammals (van der Ree *et al.*, 2004) and then translated into maps of accessible habitat (Awade & Metzger, 2008). However, few attempts have been made to model landscape resistance for bats (but see Frey-Ehrenbold *et al.*, 2013), or to integrate lighting into gap crossing models.

Measures of tree/hedge connectivity have been used to model bat activity in both rural and urban landscapes. A connectivity index for rural trees and hedgerows was developed by Frey-Ehrenbold *et al.* (2013), and used to identify a positive association between connectivity and activity patterns for three bat guilds. Their results indicate that the distance between patches impacts their likelihood of use. In addition, a connectivity measure used by Hale *et al.* (2012) found a significant effect of connected urban tree cover on bat activity, based upon the assumption that bats could cross gaps in tree cover of <40 m. In both cases, the connectivity model was developed using weightings or distance thresholds chosen to broadly reflect what was known of the species movement ecology, although the results of this study suggests that the inclusion of lighting in such connectivity models could be beneficial.

Researchers have also experimentally tested the effect of lighting on bat movement (e.g. Stone *et al.*, 2009) and

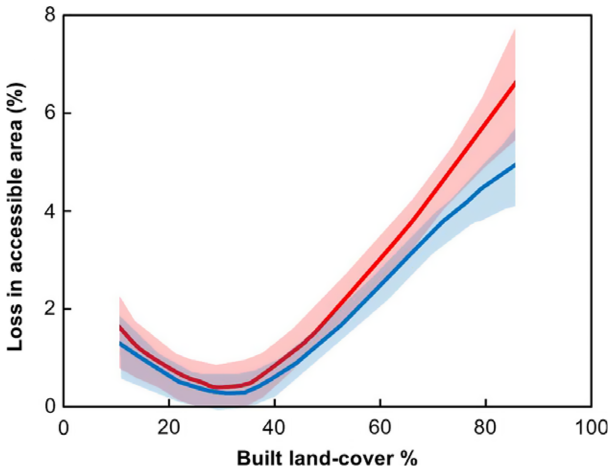

Fig. 9 The impact of lighting on the area of accessible land cover connected to urban ponds under Bright (Red) and 2009 (Blue) city lighting scenarios, compared to the levels found under a Dark City scenario.

others have modelled the effect of lighting on the movement of nocturnal species using street lamp locations to create spatially explicit lightscapes (Bennie *et al.*, 2014b); however, no studies have considered lighting thresholds for gap crossing. Stone *et al.* (2009) used experimental lighting of rural hedge lines to disrupt movement for the relatively slow flying lesser horseshoe bat (*Rhinolophus hipposideros),* demonstrating a significant barrier effect. In a later study (Stone *et al.*, 2012), they found no effect of lighting on *P. pipistrellus* despite using similar illumination ranges to our study. The study by Stone *et al.* (2012) differs to this study in two important ways: firstly in terms of the structural connectivity of the hedges/tree lines (continuous vs. fragmented), and secondly the landscape context (rural vs. urban). It is possible that illuminating a tree line to 50 lux is insufficient to disrupt the commuting behaviour of *P. pipistrellus*, but that the creation of a similarly lit gap may be enough to deter crossing. Moreover, it is possible that a small section of lit hedge in an otherwise dark rural landscape may be of little concern to the fast flying *P. pipistrellus,* whereas the perceived predation risk from crossing a lit gap in an already extensively lit urban area may be high enough to deter crossing.

Habitat accessibility and urban context

Ecological studies along urbanization gradients are relatively common and typically indicate a reduction in species richness or abundance at high levels of built density (Mckinney, 2008). However, given that many variables such as land cover and disturbance covary (Hahs & Mcdonnell, 2006; Hale *et al.*, 2013), it is often unclear which underlying mechanisms are responsible for the ecological patterns observed (Threlfall *et al.*, 2011). Here, we found that along a gradient of increasing built land cover, the area of tree canopy cover reduces whilst brightly lit surfaces increase (S2) and that these combine to increase the resistance to movement within heavily built areas.

Implications for conservation

Relating movement patterns to measures of landscape structure is desirable (Kindlmann & Burel, 2008), particularly as habitat features are often easily mapped. However, it is clear that simple maps of contiguous habitat do not necessarily correspond to functionally connected areas (Tischendorf & Fahrig, 2000) as individuals may move between habitat patches for a wide variety of reasons (Nathan *et al.*, 2008), crossing a potentially hostile matrix in the process. Networks of tree cover along with broader elements of ‘green infrastructure’ are commonly recognized in urban planning policy as ‘wildlife corridors’, although the evidence base for their efficacy is mixed (Angold *et al.*, 2006; Gilbert-Norton *et al.*, 2010). Whether such structural features actually function to reduce landscape resistance has been a much debated question in landscape ecology (Beier & Noss, 1998). Awareness of the potential impacts of habitat fragmentation (Kerth & Melber, 2009) and lighting (Stone *et al.*, 2009) on bat movement has led to a range of mitigation practices, yet in some cases, they appear ineffective (Berthinussen & Altringham, 2012). The ability to commute from roost to feeding areas is crucial to the survival of *P. pipistrellus*, and commuting distances >1 km are not uncommon (Davidson-Watts & Jones, 2006). It is therefore plausible that restrictions on movement in parts of a city could have fitness impacts at the individual level, as well as limiting the size and extent of urban populations. This highlights the need for a stronger evidence base to support work to protect and improve landscape permeability for urban bats. Whilst bat roosts within the European Union are legally protected under the EU Habitats Directive (1992/43/EEC), the level of protection afforded to commuting routes is less clear (Garland & Markham, 2007). Analyses such as those presented here could support the development of related policy, by clarifying the likely location of commuting routes and the thresholds for their disturbance. These results suggest that networks of urban trees support the movement of *P. pipistrellus*, even when they contain gaps of up to 80 m. However, it is clear that access to feeding habitats may be undermined by lighting within the surrounding landscape, even if the structural elements of the tree network remain unchanged. Although the impacts of lighting demonstrated here are subtle, the approach used to characterize barriers was conservative and lower thresholds for identifying impacts on movement may be more appropriate for conservation purposes. This is supported by the finding that individuals consistently crossed in the darker parts of the gap, even when those gaps were poorly lit, suggesting that all crossing events may be associated with costs (e.g. greater predation risks) that commuting individuals attempt to minimize. The strategic dimming of lights in the vicinity of gaps, combined with the narrowing of gaps through tree planting, might therefore be reasonable conservation measures for this species in urban areas. Such an approach may also have benefits for other bat species that are even less tolerant of lighting such as *Myotis* spp (Stone *et al.*, 2012). However, the impacts on *P. pipistrellus* of a broader scale reduction in urban lighting may be more complex, given that this species is able to exploit concentrations of its insect prey surrounding individual lamps (Blake *et al.*, 1994). Species of bats may respond to gaps (Kerth & Melber, 2009) and also lighting (Stone *et al.*, 2012) very differently; therefore, whilst this approach could be used to model the impact of lighting on landscape resistance for other species, further research is needed to identify appropriate threshold values. Similarly, it is unknown whether the barrier lux model developed here is suitable for all individuals of *P. pipistrellus*, or for different times of the night. Movement is a key component of functional connectivity, and it is important to recognize that a range of factors may influence movement events. Whilst patterns of tree cover and lighting appear to be important, further work is needed to identify how resistance may vary with different land covers or the impact of habitat quality and social structure on movement decisions.

The use of contrasting lighting scenarios to explore potential impacts on landscape resistance could be incorporated into practical conservation measures at a variety of scales. Scenarios are commonly used in sustainability research and practice to test the resilience of infrastructure, communities, resources, and natural systems to a variety of stressors (Nakicenovic & Swart, 2000; Carpenter *et al.*, 2006; Hunt *et al.*, 2012). The ecological impacts of different scenarios for land cover have been explored by other authors (Adriaensen *et al.*, 2003; Kong *et al.*, 2010; Sushinsky *et al.*, 2013), but we believe this is the first study that has explored the impacts of different urban lighting scenarios at the city scale. This approach may be useful for exploring the impact of specific proposals for changes to urban lighting (Gaston *et al.*, 2012) or tree cover (Pincetl, 2010). However, the limited knowledge of how these characteristics can change over time (Gaston *et al.*, 2012; Gillespie *et al.*, 2012) means that a broader sensitivity analysis may be required to identify network connections that are particularly vulnerable or resilient.

Given the rapid changes underway in cities, urban biodiversity is often faced with multiple ecological disruptors that may be changing simultaneously; disentangling the impacts of these disruptors presents a major challenge. For conservation to shift from a largely reactive to a more proactive approach, it must move on from detecting broad patterns in urban biodiversity to a more mechanistic understanding of the processes that drive them (Mcdonnell & Hahs, 2013). The results of this study indicate that the structural connectivity of tree cover and the levels of lighting within the intervening matrix combine to affect gap crossing behaviour for a common urban bat. In the case study city, this model predicts that as a result, habitat accessibility may reduce with increasing built density, although the potential exists for decoupling this relationship in the future. This has implications for conserving urban biodiversity in cities that are becoming brighter and more densely developed.

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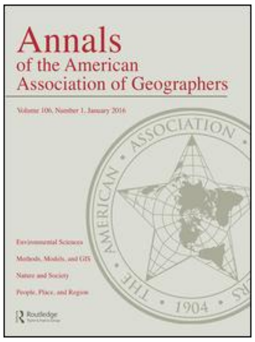
Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Information on survey gap locations and characteristics.
Figure S2. Changes in tree cover and lighting along a built density gradient.



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Are There Food Deserts in Rainforest Cities?

Gemma Davies,* Gina Frausin,* and Luke Parry†

*Lancaster Environment Centre, Lancaster University
†Lancaster Environment Centre, Lancaster University, and Universidade Federal do Pará

Food deserts have been widely studied in Western contexts but rarely in transitioning economies and never within a rainforest. The Brazilian Amazon is a rapidly urbanizing region with high levels of poverty and food insecurity, providing an ideal context in which to explore this current research gap. Within this setting, five urban centers ranging from small town to metropole are examined to explore any potential variations between urban centers of different sizes and settings. A large survey was conducted with interviews in 554 food shops, assessing shop characteristics, food availability, price, and alternative household food acquisition strategies. Methods were developed to explore food deserts, accounting for food acquisition across multiple shops within a neighborhood. Insufficient access to healthy food was estimated to be widespread (42 percent of households), with access worse in smaller towns. Unlike many previous studies, local access to healthy food was not linked to neighborhood poverty and prices were generally lower in poorer areas. High levels of nonretail sourcing of food (e.g., fruit trees, fishing) in this region might lead to an overestimation of the food access problem if only retail food provision were considered. We conclude that food deserts are widespread in the rainforest cities studied, yet we highlight the importance of understanding local retail and nonretail food contexts. Finally, we question the extent to which the traditional food desert concept can be directly applied in the context of transitioning economies. *Key Words: Amazon, food deserts, food security, poverty, urbanization.*

粮食荒漠在西方脉络中已受到广泛的研究，但在变迁经济体中的研究却为数不多，在雨林中则从未有过相关研究。巴西的亚马逊是快速城市化的区域，并具有高度的贫穷与粮食不安全，因而提供探讨当前研究阙如的理想脉络。在此一环境中，我们检视五个从小型城镇到大都会的城市中心，以探讨不同规模与环境的城市中心间的任何潜在变项。我们进行了访谈五百五十四家粮食商店的大规模调查，评估商店的特徵，粮食可及性，价格，以及家户粮食取得的另类策略。我们建立探讨粮食荒漠的方法，说明邻里中数个商店的粮食获取。未能充分取得健康粮食之情形估计当普遍（百分之四十二的家户），在较小型城镇中的取得管道则更加恶劣。与诸多先前研究不同的是，取得健康粮食的在地管道并不与邻里贫穷相连结，且在较为穷困的地区中，价格一般而言较为低廉。该区域具有高度的非零售粮食来源（例如果树、渔猎），因此若仅考虑零售粮食供给的话，将可能导致过度评价粮食取得之问题。我们于结论中主张，粮食荒漠在研究的雨林城市中相当普及，但我们仍强调理解在地零售与非零售粮食脉络的重要性。最后，我们质疑传统的粮食荒漠概念能够直接应用至转型经济体脉络中的程度。*关键词：亚马逊，粮食荒漠，粮食安全，贫穷，城市化。*

Los desiertos alimentarios han sido ampliamente estudiados en contextos occidentales, aunque rara vez en economías en transición y nunca dentro de una selva. La Amazonia brasileña es una región en rápido proceso urbanizador con altos niveles de pobreza e inseguridad alimentaria, que provee un contexto ideal donde explorar esta brecha de la investigación actual. Dentro de este escenario, cinco centros urbanos, que van desde el pueblo pequeño hasta las metrópolis, son examinados para explorar completamente cualesquiera variaciones potenciales entre los centros urbanos de diferentes tamaños y disposiciones. Se condujo un gran estudio de campo con entrevistas en 554 tiendas de alimentos, evaluando las características de la tienda, la disponibilidad de alimentos, precio y estrategias familiares para la alternativa adquisición de alimentos. Se desarrollaron métodos para explorar los desiertos alimentarios tomando en cuenta la adquisición de alimentos a través de múltiples tiendas dentro de un vecindario. Se estimó que el acceso insuficiente a alimentos saludables era en alta medida generalizado (42 por ciento de los hogares), con la inaccesibilidad mayor en los pueblos más pequeños. A diferencia de muchos estudios anteriores, el acceso local a los alimentos saludables no tenía relación mayor con la pobreza vecinal y los precios eran generalmente más bajos en áreas más pobres. Altos niveles de fuentes alimentarias sin menudeo (e.g., frutales, pesca) en esta región podrían conducir a una sobreestimación del problema del acceso a los alimentos si solo se considerara la provisión de alimentos al detal.

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Concluimos que los desiertos alimentarios pululan en las ciudades estudiadas de la selva pluvial, aunque destacamos la importancia de entender los contextos locales del comercio local al menudeo o al por mayor. Finalmente, cuestionamos la extensión con la cual el concepto tradicional de desierto alimentario puede ser aplicado directamente en el contexto de las economías en transición. *Palabras clave: Amazonia, desiertos alimentarios, seguridad alimentaria, pobreza, urbanización.*

Food deserts have been widely studied in Western contexts, rarely within the Global South, and never in a rainforest setting. This article therefore explores food deserts in a nontraditional context, focusing on a transitioning economy undergoing rapid urbanization and its associated food transition. The study also differs from many traditional applications of the food desert concept in that, whereas supermarkets have traditionally been significant in food desert studies, this region has not yet experienced widespread penetration of large supermarket chains.

Food Security and Food Deserts

Food insecurity affects approximately 1 billion people worldwide (Godfray et al. 2010; Piperata et al. 2013) but is only partly driven by food production, with households becoming food insecure when lacking access to affordable, nutritious, and safe food (Pinstrup-Andersen 2009). Household food security can lead to malnutrition, immune system deficiencies, health problems, and developmental consequences (Caulfield et al. 2004; Dubois et al. 2006; Seligman, Laraia, and Kushel 2010; Rodríguez, Cervantes, and Ortiz 2011; Black 2012; Lee et al. 2012). The association of poverty and malnutrition with poor cognitive development and educational development in children contributes to ongoing, intergenerational cycles of poverty (Grantham-McGregor et al. 2007). Given the immediate and long-term effects associated with food insecurity and malnutrition, it is therefore imperative to identify those most at risk (Piperata et al. 2013).

Food deserts were first identified in the 1990s to describe areas with poor access to the affordable food necessary for a healthy diet (Beaulac, Kristjansson, and Cummins 2009; LeClair and Aksan 2014). Hence, food deserts represent both physical and economic barriers to accessing healthy food (Reisig and Hobbiss 2000) and relate closely to food insecurity. In the United Kingdom and United States, food deserts first emerged as large supermarkets began to dominate food provision, leading to the closure of smaller food shops and disadvantaging carless households who became less able to access affordable food (Cummins and Macintyre 2002; White and Hamm 2014). Later the subsequent withdrawal of supermarkets from some deprived areas further exacerbated the presence of food deserts (Raja, Ma, and Yadav 2008; Russell and Heidkamp 2011). By contrast, this study examines food deserts within a transitioning economy where supermarkets are yet to widely penetrate retail food provision. As incomes increase, it might be expected that the level of service provided by food retail will also grow. There are significant differences between studies regarding how food deserts are defined, with some authors qualifying them as specifically urban (Cummins and Macintyre 2002) and others arguing that they must be located within areas with high deprivation or poverty (Jiao et al. 2012; Battersby and Crush 2014). Numerous studies identify access to supermarkets as a key determinant of food deserts (Jiao et al. 2012; LeClair and Aksan 2014; Pine and Bennett 2014), yet this approach potentially underestimates the value of smaller stores in the provision of healthy food, especially where larger stores are absent (Ver Ploeg et al. 2009; Martin et al. 2014).

People's food choices are strongly influenced by availability within their immediate neighborhood (Walker, Keane, and Burke 2010). Consequently, in areas where unhealthy food options are the most prevalent and affordable, household diets tend to worsen (Hendrickson, Smith, and Eikenberry 2006; Gartin 2012; Alviola et al. 2013). Insufficient access to affordable, healthy food in food deserts has potentially serious consequences for both health and development (Moore and Diez Roux 2006; Beaulac, Kristjansson, and Cummins 2009; Larson, Story, and Nelson 2009; Walker, Keane, and Burke 2010; Cummins 2014). Greater understanding of the spatial nature of food deserts will help develop policies to improve equitable access to healthy food, thus alleviating some health inequalities (Larson, Story, and Nelson 2009; Alviola et al. 2013).

Food Deserts in the Transitioning Economies

Due to widespread poverty and food insecurity, examining food deserts in transitioning economies is more pertinent than in Western areas where it has usually been applied. To date, very few studies have attempted to investigate food deserts in the Global South (Gartin 2012; Duran et al. 2013; Battersby and Crush 2014) despite being inhabited by the vast majority of the world's urban poor (Mitlin and Satterthwaite 2012). It remains both unclear to what extent urban food deserts are present in transitioning economies of the Global South and, moreover, whether traditionally defining food deserts in terms of retail access is compatible with different food cultures, livelihoods, food acquisition strategies, and environments.

Food retail contexts vary throughout the Global South and are often very different to Western contexts. Although supermarkets have been portrayed as a cause of (Guy, Clarke, and Eyre 2004) and solution to (Morland, Wing, and Diez Roux 2002; Walker, Keane, and Burke 2010) food deserts, the penetration of supermarkets in the Global South is highly variable (Gartin 2012; Duran et al. 2013; Battersby and Crush 2014). Where supermarkets are present, those in lower income areas often stock a less healthy range of products, thus failing to improve healthy food access (Duran et al. 2013; Battersby and Crush 2014).

Sufficient income to access food is a greater challenge to food security than food availability (Crush, Frayne, and Pendleton 2012). High levels of poverty and inequality exist across the cities of the Global South, making households vulnerable to food insecurity and food deserts (Acquah, Kapunda, and Legwegoh 2014; Frozi et al. 2015). Small and medium-sized urban centers in the Global South have higher poverty rates than larger urban centers (Ferré, Ferreira, and Lanjouw 2010). This article, therefore, includes an urban metropolis alongside smaller urban centers, enabling a holistic overview. Throughout the Global South a variety of food sourcing strategies are employed that could help alleviate the impact of living in food deserts. It is important that these are considered in the context of food deserts. In southern African cities, alternative food sourcing strategies are critical for food security (Crush, Frayne, and Pendleton 2012), with alternative food sources such as urban agriculture and informal rural–urban food transfers supplementing retail food provision (Frayne, McCordic, and Shilomboleni 2014; Pendleton, Crush, and Nickanor 2014). Credit provided by smaller stores is a further possible coping strategy employed (Gartin 2012).

The study examines variation in food deserts within a transitioning economy, examining variation between urban centers of different sizes from large metropole to small town, while also considering the importance of alternative food sourcing strategies. The relationship between accessibility and affordability of healthy food is explored across these urban centers, in relation to both income poverty and shop type. The specific research questions asked are as follows:

1. How widespread are food deserts in a rainforest metropolis and smaller urban centers?
2. Are food deserts more common in poorer neighborhoods?
3. Is the location of food deserts related to the distribution of different shop types or due to locally determined differences in food prices?
4. To what extent do urban households acquire food through methods other than shop purchases (e.g., through planting and harvesting)?

Asking these questions is important to understand the extent to which food deserts affect households within urban centers of the rainforest and which factors (e.g., food provision or low income) are related to households living in a food desert. Understanding these factors might ultimately help policymakers better target decisions to improve the food security of the most vulnerable.

Brazilian Amazon

Despite Brazil's progress in alleviating poverty, household food insecurity, income inequality, and malnutrition, rates of each remain high, especially in the Amazon. Coupled with rapid urbanization and a shift toward increased reliance on purchased food, these factors make the Brazilian Amazon an important context in which to critically apply the food desert concept. Within the northern region of Brazil where the Amazon rainforest is located, 41 percent of households are estimated to experience food insecurity (Instituto Brasileiro de Geografia e Estatística [IBGE]). Of the households, 11 percent live in extreme poverty, with a further 22 percent in the north living in absolute poverty (IBGE 2013). Brazil's income inequality ranks among the highest worldwide (Rasella, Aquino, and Barreto 2013), with a Gini coefficient of 0.54 (IBGE 2013), with malnutrition greatest in areas where income inequality is highest (Larrea and Kawachi 2005; Pathak and Singh 2011).

Attempts to alleviate low food security and poverty for some of the poorest households have been made though the government strategy *Fome Zero* (Zero Hunger), which commenced in 2003. A key element of this strategy has been the introduction of a conditional cash transfer system, *Bolsa Família* (Wetzel 2013; World Bank 2016). Despite this assistance, families qualifying for and receiving the *Bolsa Família* are still found to be four times more likely to suffer severe food insecurity (Segall-Corrêa et al. 2009). A case study recording dietary change between 2002 and 2009 highlights a food transition contributed to by the *Bolsa Família*. It indicates that the *Bolsa Família* has encouraged purchasing of a greater proportion of food, resulting in a change of diet consisting of increased protein intake, but an overall decline in calories consumed (Piperata et al. 2011). During this period the principal food energy sources shifted from local foods (manioc flour, açaí [a local fruit], fish, and other fruits) to purchased foods (beans, rice, and crackers) while maintaining consumption of açaí (Piperata et al. 2011).

The Brazilian Amazon is a transitioning economy, accompanied by associated rapid urban expansion. The population of Manaus, for example, doubled in size between 1991 and 2015 (IBGE 2016). Although it is unclear what food access in Amazonia was like in the past, this study provides a baseline against which future changes can be measured. Within the Brazilian Amazon, large supermarkets have only begun to penetrate within large cities, such as Manaus, where urbanization and economic transition are more advanced. The majority of foodstuffs are still distributed through a network of small shops run as livelihoods for poorer families. Methods for identifying food deserts therefore need to be adjusted to reflect the local food context. Small local food shops potentially offer some advantages over supermarkets, including more convenient locations, selling in small quantities, and offering credit (White and Hamm 2014). Evidence suggests that nonretail food acquisition is also important for food security in Amazonia. Plots of land for urban gardens or rural agriculture are important for subsistence and exchange of food between rural and urban areas (WinklerPrins and de Souza 2005). Most include fruit trees, although fewer include culinary plants due to a lack of culinary interest in vegetables. In Santarém, for example, 43 percent of households kept some animals, mainly chickens and ducks, providing eggs and some meat (Winklerprins 2002). Fishing is a further important strategy for food sourcing. Nardoto et al. (2011) found that in Iranduba, 38 percent of those interviewed had a preference for fish, rather than commonly sold frozen chicken, because people could catch the fish themselves. Research in other riverine urban centers confirms the importance of fishing and hunting as food acquisition strategies for urban households. Here bush meat was consumed monthly by 44 percent of the households surveyed. Although consumption of bush meat and many types of freshwater fish causes concerns for species conservation (Parry, Barlow, and Pereira 2014), it could be significant in reducing household food insecurity. To cope with household food shortages, 43 percent of respondents to the national Pesquisa Nacional de Demografia e Saúde survey in 2013 claimed to have bought food on credit, with a further 28 percent borrowing food from family and friends (IBGE 2014).

This article focuses on urban centers within the Brazilian Amazon, specifically within the state of Amazonas. The state has rapidly urbanized and by 2010, 51 percent of the state's population lived within the urban metropolis of Manaus, 28 percent in smaller urban centers, and 21 percent in rural areas. Urban poverty in Amazonas is high, with 34 percent of households in Manaus and 59 percent of households in smaller urban centers living in absolute poverty (IBGE 2010).

Method

The five urban centers studied include the metropolis of Manaus (population = 1.8 million people) and four smaller cities in the surrounding area. They are all road-connected and were: Manacapuru (60,000 people, 96 km from Manaus), Iranduba (15,000 people, 39 km), Presidente Figueiredo (11,000 people, 122 km), and Novo Airão (9,500 people, 196 km; IBGE 2010).

Data Acquisition

During March and April 2015, 554 shops were surveyed ranging from large supermarkets to small shops and vendors of individual food products. These included all food shops found within the urban centers of Novo Airão, Iranduba, and Presidente Figueiredo and a sample of four neighborhoods in each of the larger urban centers of Manacapuru and Manaus. Sample neighborhoods were selected to represent neighborhoods along a gradient from high to low deprivation within the urban center. The selected neighborhoods were typically composed of three or four census sectors (each populated by several hundred households). The total population living within the areas surveyed in each of Manaus and Manacapuru was just over 15,000, comparable to the population size of the largest of the small urban centers within the study.

Four types of data were collected at each shop: location and shop characteristics, availability of a selection of different foodstuffs, price of available food stuffs, and shop owners' perceptions of customers' alternative food sourcing strategies. The food products surveyed were selected as being commonly consumed within the study area, with knowledge of consumption based on field observation and consultation with a local expert. Nutritional information (e.g., saturated fat and salt content) was obtained from the *Tabela Brasileira de composição de alimentos* (Núcleo de Estudos e Pesquisas em Alimentação [NEPA] 2011) and used to exclude unhealthy food products (e.g., low in nutrients and high in sodium and saturated fat). Although all fruit and vegetable availability was recorded, only a limited selection of staple foods and sources of animal protein was selected for the survey to limit the length of the questionnaire and encourage engagement by all shop owners.

Road and path data were derived from Open Street Map (OSM) data, downloaded from http://download.geofabrik.de/. Additional roads or paths evident either on the ArcGIS Imagery base map or identified in Google Earth were also added to the data set. Google Street View was used to help identify segments of road or path that appeared to be residential. Although care was taken to ensure that the road and path locations and residential classification were complete, it is acknowledged that this cannot be guaranteed.

Spatial Analysis

Methods and thresholds used to identify food deserts vary considerably. For example, the U.S. Department of Agriculture (USDA 2015) identified food deserts as census tracts where at least a third of the population live more than a mile from the nearest supermarket or large grocery store and with a poverty rate of at least 20 percent. Alternatively, Jiao et al. (2012) considered a ten-minute drive, bus, cycle, or walk time from supermarkets. LeClair and Aksan (2014) adopted thresholds of half a mile from a supermarket or a five-minute walk from smaller food shops; and Raja, Ma, and Yadav (2008) consider five-minute travel times to food shops. All of these approaches, however, are only able to approximate the true neighborhood area an individual or household traverses (Kwan 2012). Numerous studies have relied on store type to estimate food availability; however, the same store type might sell different products (Franco et al. 2008). To measure access to affordable, nutritious food, the availability and price of products is required for all food shops within a neighborhood (Ver Ploeg et al. 2009).

In this study, walking was assumed as the main mode of transport used when obtaining food, with poor families having little access to transport. Private vehicle access is low (typically one per three households; IBGE 2016) and public transport limited to major routes and often unreliable (field observation). The maximum walking distance to a shop was considered to be 250 m, based on a travel time threshold of five minutes (LeClair and Aksan 2014) and typical walking speed of 3 km/h^{-1} in the tropics (field observation). This reflects observations during fieldwork that the majority of food shopping happened on a daily basis and was often undertaken by children. As with Raja, Ma, and Yadav (2008), this distance threshold is not intended to be an absolute measure of how far people are willing to travel, or by what means, but rather a representative measure by which households can be compared.

Spatial analysis was undertaken using a geographic information system (GIS), with the software ArcGIS 10.2.2. Insufficient access to healthy food (i.e., spatially within a food desert) was defined as household locations without access within 250 m from home to all of the staple foods (manioc flour, beans, and bread), at least five different types of fruit or vegetable, and a variety of affordable healthy sources of animal protein (at least three of the surveyed products: tinned beef, meat on the bone, chicken and eggs). To ensure distance calculations accounted for where people could walk, a 15-m buffer around the roads and paths was applied as an analysis mask. Cost distance surfaces were created and reclassified for each food product to show all areas where that product could be purchased within 250 m. A further analysis mask was subsequently applied constraining analysis only to areas where residential households were present. For each food group (staples, animal protein, fruit and vegetables) the number of products available at a given location was then added together. Each group was then reclassified to identify whether the minimum defined threshold was met. Areas with insufficient access to healthy food were then identified by combining the groups together. To estimate the number of households without access to healthy food, the proportion of the residential area within each census sector defined with insufficient access to healthy food was calculated and multiplied by the number of households within the census sector. Census sectors contain roughly even numbers of households (an average of 184 households per urban census sector in Amazonas state).

Shop Types

The survey included questions about the presence or absence of different services including whether they accepted credit cards, employed nonfamily members, had shopping trolleys, had electricity, provided direct access to the products, had a computerized till, and had more than one till. Exploratory principal components analysis was used to assess the relationships among different shop surveys, linkages between service provision, and estimated shop width (as a proxy of shop size). Results showed that there was a tendency for cooccurrence of specific services in groupings of similar shops. These results were used to develop a typology of shops, ensuring that there were sufficient sample sizes (e.g., at least a few dozen) in each category to enable them to be used as fixed factors in statistical models. Although width was loosely correlated with service provision, there was sufficient variation in service among similar-sized shops to warrant a typology based on services. Consequently, four categories of shop were defined, and these categories were used as predictor variables in statistical models. Type 1 shops are those with none of the services listed; these are small family-run shops with products generally served to customers through a window. Type 2 are those with only one of the services listed. Type 3 shops have between two and four of the services. Type 4 shops have five or more of these services. Self-determined shop type

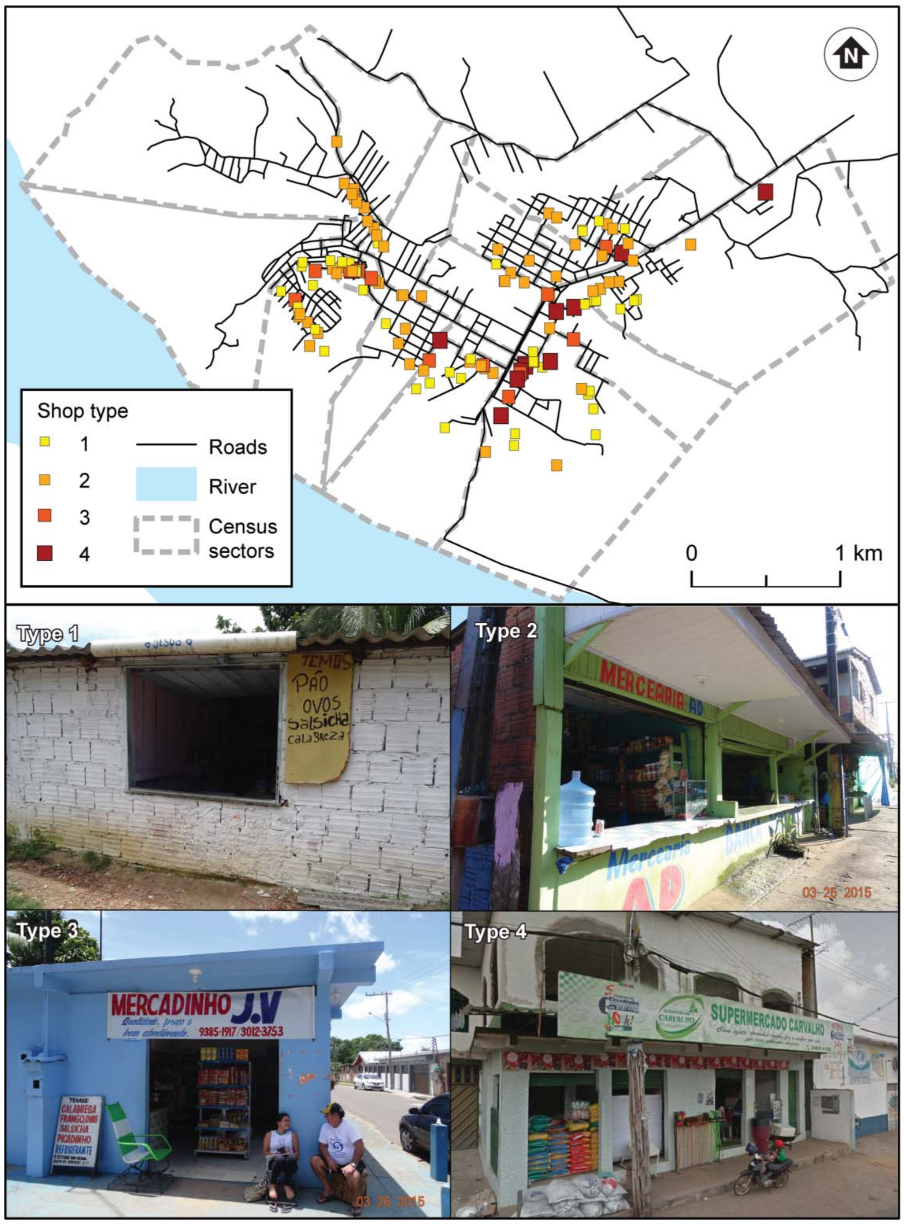

Figure 1. Distribution of shop types within Iranduba. Photographs illustrate each of the shop types. Shop types are defined in terms of number of services and facilities available, ranging from very basic (Type 1) to more sophisticated (Type 4). (Color figure available online.)

was recorded during interviews, using local names such as *mercado*, *mercearia*, and *taberna* (de Oliveira Moraes and Schor 2010). There were significant inconsistencies in these labels and thus a new typology was adopted. Figure 1 illustrates the distribution of shop types for an example urban center, Iranduba.

Healthy Food Basket

To enable analysis of price differences, a basket of healthy food items (Table 1) was defined. A subset of products was selected from the healthy food products surveyed, including those items for which standardized prices were available. It was necessary to exclude some of the surveyed food products at this stage (e.g., bread and bananas) as it was not possible to accurately standardize their prices to comparable units. Basket quantities represent expenditure on these food items during one week for an average-sized household (four people), using data from the IBGE 2008–2009 consumer expenditure survey (*Pesquisa de Orçamentos Familiares*, IBGE 2010) as a guide to estimate quantities of each food product purchased. Although the basket contains a mixture of staples, protein sources, and fruit and vegetables, it does not attempt to demonstrate total food range, quantity, or expenditure required for a healthy diet.

Statistical Analysis

All statistical analyses were conducted in the R platform version 3.2.3 and using the additional packages FactoMineR and rpart (for exploratory principal components analysis and development of the shop classification). For the shop-scale availability models (0/1), general linear models (GLMs) with a binomial error distribution (a logistic model) were used. The model predicting the number of fruits available, however, used a Gaussian error structure (following a normal distribution). Predictor variables included shop type, percentage of households living in absolute poverty ($\leq$0.5 minimum salaries per capita per month; see Parry, Barlow, and Pereira 2014), and municipality as a fixed effect, which assessed significant differences relative to the town of Iranduba, the control. For the price models (predicting foodstuff-specific and basket prices), GLMs with Gaussian error structures were used, as assumptions of normality were met. Price models also included shop type, income poverty, and municipality as predictor variables.

Table 1. Quantities, availability, and price of foods included in the food basket

Food type	Quantity included	Number of shops available	Average price (R$)	*SD* price (R$)
Manioc flour	1.5 kg	495	5.65	2.17
Beans	1.5 kg	323	6.54	1.25
Chicken	1.5 kg	338	8.56	0.79
Tinned beef	107 g	460	1.81	0.43
Eggs	1 egg	492	0.36	0.05
Onions	220 g	377	1.25	0.41
Tomatoes	180 g	251	1.12	0.20

Results

How Widespread Are Food Deserts in a Rainforest Metropolis and Smaller Urban Centers?

In this article, insufficient access to healthy food is defined in terms of spatial availability of food products within 250 m of a household (see methods). This equates to a spatial definition of a food desert before consideration of price, income, or any alternative food sources. Table 2 shows that a total of 41 percent of the households in our survey area were found to live in locations with insufficient access to a healthy range of food. In two of the smaller cities, Iranduba and Presidente Figueiredo, 50 to 60 percent of households had insufficient access to healthy food, whereas 38 percent had insufficient access in Novo Airão and less than a third in the larger city of Manacapuru and the metropolis of Manaus (28 percent and 32 percent, respectively). Across all urban centers, the major constraint in accessing healthy food was insufficient access to a range of fruit and vegetables. Overall, 38 percent of households lacked access to five or more different fruits or vegetables. Although the staple carbohydrate, manioc flour, was widely available, availability of bread and dried beans was more limited and overall a fifth of household (ranging from 14–32 percent across cities) lacked access to staple foods. In contrast, access to sufficient sources of animal protein was generally good (7–17 percent of households lacking access).

Are Food Deserts More Common in Poorer Neighborhoods?

A high proportion (42 percent) of households in the area surveyed live in absolute income poverty

Table 2. Estimated households without access to specified food groups

Urban center	Survey				Percentage of households lacking sufficient			
	Type	Census sectors	Shops	Households	Fruits and vegetables	Animal protein	Staples	Healthy food
Iranduba	Full	17	132	3,689	49	16	23	50
Novo Airão	Full	13	93	2,081	35	9	22	38
Presidente Figueiredo	Full	23	79	2,918	50	7	32	60
Manacapuru	Sample	15	178	3,236	27	13	14	28
Manaus	Sample	16	72	3,521	30	7	14	32
Total		84	554	15,642	38	11	20	41

(IBGE 2010). There is a highly variable relationship, however, between income poverty and the access to sufficient healthy food (Figure 2). Although cooccurrence of high levels of poverty (≥67 percent of households) and insufficient access to healthy food was rare (two sectors on the outskirts of Iranduba), there were many census sectors in which there was very poor access to healthy food (≥67 percent of households) and intermediate levels (33–66 percent of households) of poverty. There were two cases (outskirts of Manacapuru) where high levels of poverty cooccurred with moderate access to healthy food and many examples where intermediate poverty occurred with intermediate access to healthy food. Few census sectors (mostly in Manaus) experienced both low levels of poverty and a low percentage of households with insufficient access to healthy food. Half of all census sectors studied had a low percentage of households with insufficient access to healthy food (1–33 percent), with a moderate number of households living in absolute poverty (33–67 percent).

Is the Location of Food Deserts Related to the Distribution of Different Shop Types or Due to Locally Determined Differences in Food Prices?

Despite an inconsistent relationship between poverty and food access, the number and composition of shops varied strongly according to poverty (Figure 3). In the least poor areas, there is relatively little difference between types in the number of shops per hundred households. In areas with 33 to 67 percent of households living in poverty, the number of Type 1 and 2 shops per 100 people more than doubles, accompanied by smaller increases in Type 3 and 4 shops. In areas with the highest levels of poverty, the number of Type 1 and 2 shops increases again, yet here the presence of Type 3 and 4 shops almost disappears, with 98 percent small family-run shops of Type 1 or 2. The overall number of stores averages five per hundred households where poverty is greater than 67 percent, compared to only one and a half per hundred households where poverty is less than 33 percent.

Availability of food items was generally greater in higher service level shops, although there were exceptions (Table 3). The highest service shops (Type 4) were significantly more likely to stock each of the food items than Type 1 shops. Type 3 shops were significantly more likely than Type 1 stores to stock most of the food items, although, interestingly, availability of manioc flour, bread, and eggs was not significantly different. Type 2 shops were significantly more likely than Type 1 shops to stock all foodstuffs apart from meat. When controlling for shop type, shops in poorer areas were significantly more likely to sell manioc flour, chicken, tinned meat, eggs, and beans and significantly less likely to sell bananas or other fruits. There were significant differences in the availability of foodstuffs across urban centers and the availability of six of the foodstuffs was significantly better in comparable shops of Manaus than in Iranduba, the control. In Manacapuru, three items had greater availability than in Iranduba, whereas one item (frozen chicken) was less available. There were only weakly significant differences in availability between Iranduba and Novo Airão.

Although there was no significant difference in basket price between shop Types 1, 2, and 3, prices were generally cheaper in larger, more sophisticated stores relative to smaller, simpler stores (Table 3). The price of a healthy food basket was significantly cheaper (R$2.13 less) in Type 4 shops than in the most basic ones (Type 1; Table 3; Figure 4A). The reason for this price differential is unknown, although it might relate to economies of scale in shop purchasing power. The price of a healthy food basket was significantly cheaper in poorer areas

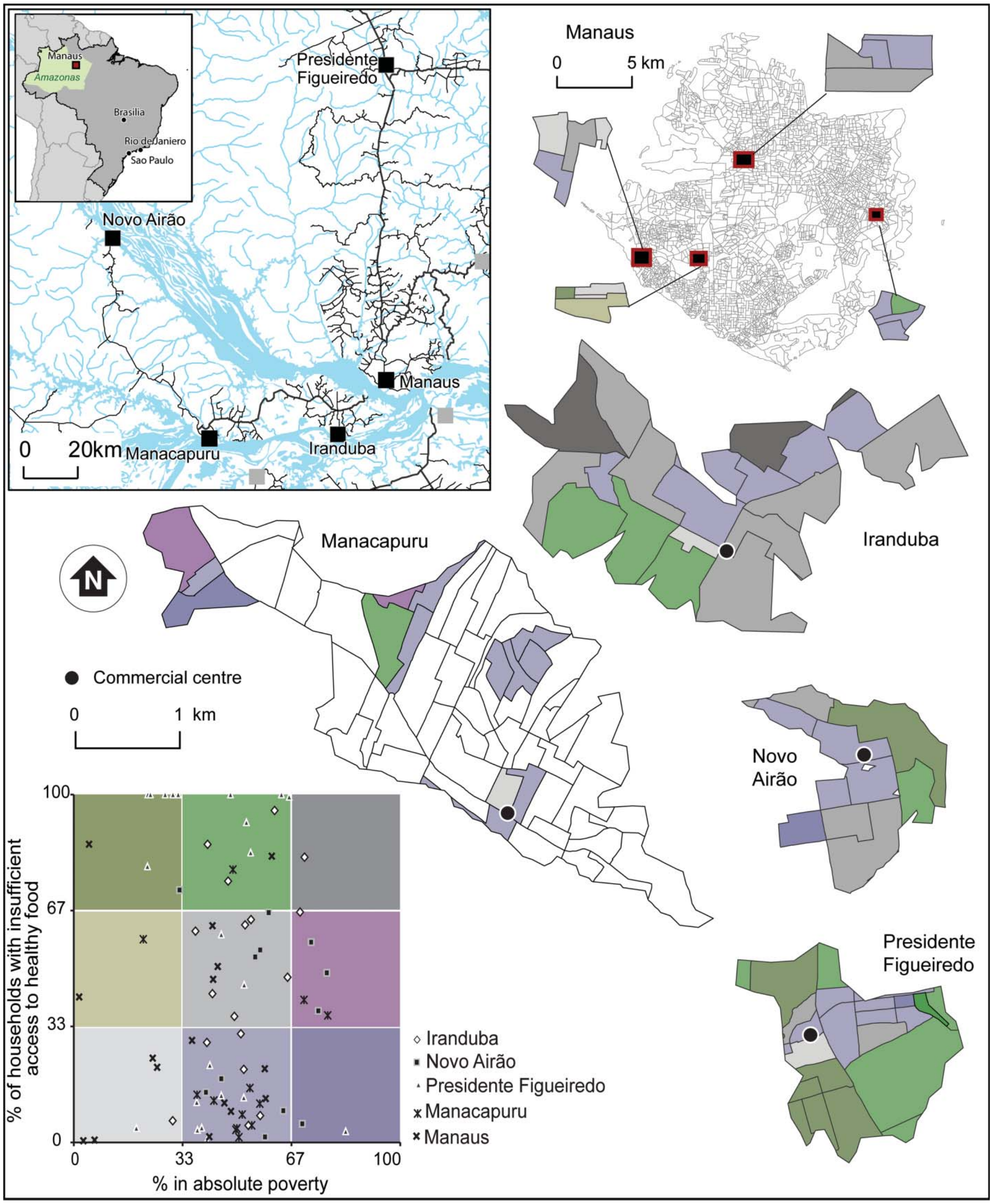

Figure 2. Relationship between absolute poverty and prevalence of households with insufficient access to healthy food, per census sector in the studied urban centers. (Color figure available online.)

when controlling for shop type, at around R$0.40 less for each 10 percent increase in absolute poverty (Table 3; Figure 4B). Despite lower prices, however, relative affordability of this food basket is much lower in low-income neighborhoods. For example, the basket of R$33 in the most affluent sector surveyed would cost only 4.2 percent of average weekly income in that sector, compared to a lower basket price of R$26, requiring 80 percent of average income in the poorest sector (Figure 5). Compared to prices in Iranduba, a food basket was significantly more expensive in Manacapuru (R$5 more) and Novo Airão and Presidente Figueiredo (R$3 more in each). There were also significant variations in the price of specific foodstuffs, according to shop type, poverty, and urban center. Beans

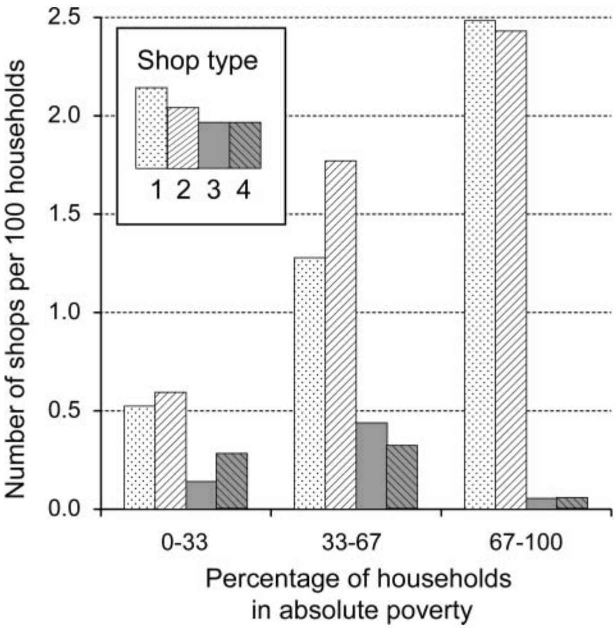

Figure 3. Access to shop types in studied census sectors of Manaus, Manacapuru, Novo Airão, Iranduba, and Presidente Figueiredo. Types defined in terms of number of services and facilities available, ranging from very basic (Type 1) to more sophisticated (Type 4).

and frozen chicken were significantly cheaper in Type 4 shops compared to Type 1, whereas greens (cheiro verde) were more expensive. Type 1 shops were significantly more expensive than all other shop types for tinned meat, eggs, and onions. The price of manioc flour, meat on the bone, and tomatoes did not vary significantly among shop types. The price of toasted manioc flour was much cheaper in Iranduba compared to Manacapuru (costing R$2.51 more per litre), Manaus (R$1.08 more), Novo Airão (R$2.12 more), and Presidente Figueiredo (R$1.55 more). Manioc flour, eggs, and greens were significantly cheaper in poorer areas. For instance, manioc flour was R$0.20 cheaper.

To What Extent Do Urban Households Acquire Food through Methods Other Than Shop Purchases?

Although the full contribution of alternative food sourcing strategies to household food security is not clear, results do confirm many alternative strategies are used (Table 4), the most important of which are having fruit trees at home and fishing. Fruit trees were found to be important in all urban centers, with 56 percent of shop owners estimating at least half of their customers had fruit trees at home. In addition, 51 percent of shop owners estimated at least half of their customers fished. This number was greatest in small urban centers situated on a river (Novo Airão and Iranduba), compared to just 11 percent in Manaus. Among shop owners, 22 percent thought that at least half their customers kept chickens and 12 percent thought that at least half went hunting. Growing vegetables at home was the least common strategy but, importantly, 41 percent of shop owners estimated that at least half of households grew food in rural plots.

Field observations identified that many poorer households bought food in small quantities on a regular basis. Many shops help facilitate this. For example, processed sausages, a popular although unhealthy component of many household diets, are sold in packs of ten to sixteen sausages, yet many shop owners split these into smaller quantities for sale. Other products (e.g., onions) were halved.

Discussion

In this article, food desert coverage and the extent to which this concept is relevant to a transitioning economy was explored in rainforest cities. The study context in the Brazilian Amazon provided an ideal opportunity to assess the presence of food deserts in a region where large supermarket chains are yet to dominate. By sampling a large number of shops across five urban centers of different sizes, comparison across scales and between urban centers was possible rather than just within centers. Exploring both availability and price of a range of foodstuffs across all shop types enabled a full picture of retail food availability to be considered. Importantly, the method employed is able to identify poor access to specific food groups or individual products. The key findings in relation to the research questions posed in this article were as follows:

1. Food deserts (defined as areas with insufficient retail access to healthy food) were widespread within the urban centers studied, largely due to a lack of fruit and vegetables sold.
2. Food deserts were no more likely to occur in poorer areas than in less poor areas.
3. Food retail was dominated by a network of small shops with few facilities, with higher shop densities in the poorest neighborhoods. Food prices were generally lowest in poorer areas.

Table 3. Models of food availability (on sale or not) and food prices (R$) in 554 food outlets in Manaus, Manacapuru, Novo Airão, Iranduba, and Presidente Figueiredo

Models of food availability

Item	*df*	R^2	Shop Type 2	Shop Type 3	Shop Type 4	Poverty	Manacapuru	Manaus	Novo Airão	Presidente Figueiredo
Manioc flour	575, 583	0.08	0.59	0.8 *ns*	2.66*	0.04**	0.35 *ns*	2.04***	−0.01 *ns*	1.14*
Beans	575, 583	0.10	0.87***	1.5***	3.17***	0.02	0.16 *ns*	0.42 *ns*	0.01 *ns*	0.71*
Bread	575, 585	0.04	0.64**	0.28 *ns*	1.32***	0 *ns*	0.83***	0.36 *ns*	0.53	−0.23 *ns*
Chicken	575, 583	0.16	1.25***	2.31***	3.8***	0.02*	−0.62*	−0.22 *ns*	−0.36 *ns*	0.12 *ns*
Meat	575, 583	0.24	−0.08 *ns*	1.08	2.67***	−0.01 *ns*	−0.62 *ns*	0.53 *ns*	0.17 *ns*	0.36 *ns*
Tinned meat	575, 583	0.09	0.45	1.09*	3.26**	0.03**	0.49 *ns*	1.13**	−0.56	1.23**
Eggs	575, 583	0.09	0.61	0.81 *ns*	1.54*	0.04**	1.12**	2.04***	−0.15 *ns*	1.13*
Onions	575, 583	0.10	1.03***	1.27***	2.46***	0 *ns*	−0.03 *ns*	−0.31 *ns*	0.28 *ns*	0.4 *ns*
Tomato	575, 583	0.12	1.17***	1.46***	2.76***	0 *ns*	0.01 *ns*	0.06 *ns*	0.11 *ns*	0.62
Pepper	575, 583	0.09	1.06***	1.28***	2.1***	0 *ns*	0.27 *ns*	0.7*	−0.08 *ns*	0.43 *ns*
Greens	575, 583	0.11	1.13***	1.2***	1.65***	0 *ns*	0.32 *ns*	1.38***	0.15 *ns*	1.24***
Banana	575, 583	0.09	0.72**	0.71	1.37***	−0.03***	0.36 *ns*	0.32 *ns*	0.63	−0.7
Fruits (n)	575, 583	0.17	0.68***	0.79***	1.29***	−0.01**	0.16*	0.25**	0.16	0.1 *ns*

Models of food prices

Item	*df*	R^2	Shop Type 2	Shop Type 3	Shop Type 4	Poverty	Manacapuru	Manaus	Novo Airão	Presidente Figueiredo
Manioc flour	514, 522	0.40	−0.15 *ns*	−0.24 *ns*	0.07 *ns*	−0.02***	2.51***	1.08***	2.12***	1.55***
Beans	338, 346	0.04	−0.06 *ns*	−0.15 *ns*	−0.37*	−0.01 *ns*	0.24	−0.13 *ns*	0.10 *ns*	0.20 *ns*
Chicken	349, 357	0.21	−0.09 *ns*	−0.06 *ns*	−0.49***	0 *ns*	−0.06 *ns*	−0.36***	0.03 *ns*	0.26**
Meat	48, 56	0.22	−1.10 *ns*	−1.81 *ns*	0.86 *ns*	−0.03 *ns*	0.55 *ns*	−0.68 *ns*	0.90 *ns*	−0.15 *ns*
Tinned meat	464, 472	0.15	−0.24***	−0.40***	−0.70***	0 *ns*	0.09 *ns*	−0.03 *ns*	−0.22*	0.13 *ns*
Eggs	510, 518	0.17	−0.03	−0.07**	−0.07**	0*	0.07***	0.15***	0 *ns*	0.08**
Onions	322, 330	0.06	−0.45**	−0.45*	−0.59**	0 *ns*	0.24 *ns*	0.45*	−0.07 *ns*	0.31
Tomatoes	268, 276	0.02	−0.14 *ns*	0.09 *ns*	−0.07 *ns*	0 *ns*	0.25 *ns*	0.36 *ns*	0.31 *ns*	0.29 *ns*
Greens	148, 156	0.42	0.10 *ns*	0.09 *ns*	0.30**	−0.01***	0.02 *ns*	0.27*	0.57***	0.17
Basket price	177, 185	0.28	−0.62 *ns*	−1.09 *ns*	−2.13**	−0.04*	4.56***	0.87 *ns*	2.96***	2.76***

Note: *ns* = $p > 0.05$ (i.e., not significant); * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$.

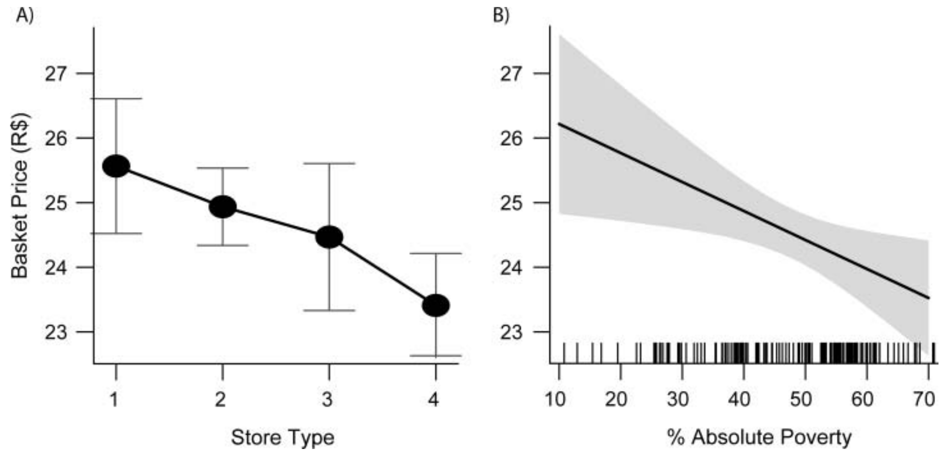

Figure 4. Relationship between (A) basket price and store type and (B) basket price in individual shops and the percentage of households within 250 m living in absolute poverty.

4. Alternative food sourcing strategies such as fruit trees and fishing appear to have significant roles in food provision. This might challenge the applicability of conventional food desert definitions within transitioning economies, but further research is required. Our main findings are now be considered further along with their policy implications.

Presence of Food Deserts

Despite observing high shop density, local access to a sufficient range of healthy food products, regardless of

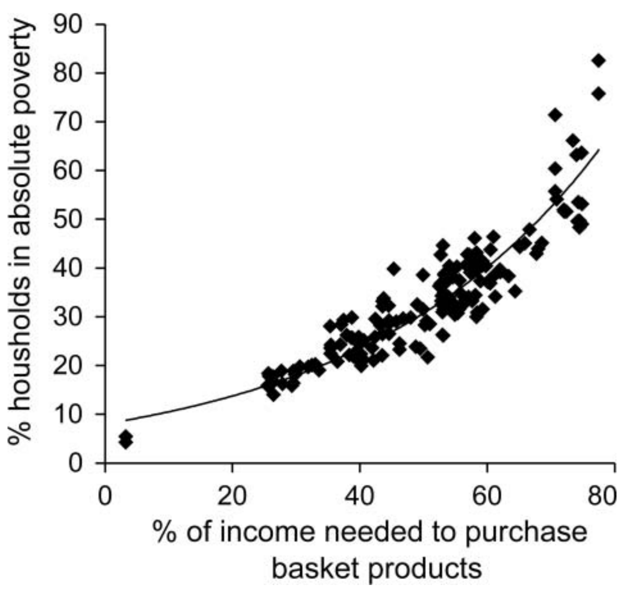

Figure 5. Relationship between the percentage of weekly household income required to purchase the sample basket and the percentage of households living in absolute poverty. (Calculated for 165 shops where all basket products were available. Demographic data calculated as the average for the area of 250 m around the shop.)

affordability, was found to be insufficient in many areas. The defined thresholds for both distance and food products included in the method are only illustrative and cannot encapsulate all nutritional needs or household purchasing or coping strategies. Nevertheless, these results indicate that there is significant scope to improve access to some food products and, in particular, fruit and vegetables. A lack of access to fruit and vegetables is of particular concern, as Brazil's consumption only reaches half of the World Health Organization–recommended levels (Cobayashi et al. 2014). Evidence both from shopkeeper responses within this study and elsewhere (WinklerPrins 2002) suggests, however, that fruit is often sourced from fruit trees at home and might to some extent supplement a lack of retail provision. There is less evidence of alternative provision of vegetables. Understanding which food products cause food deserts to be defined can both help direct further research and help guide policy.

In contrast to most previous studies (Duran et al. 2013), neighborhood poverty in urban Amazonia was

Table 4. Alternative food sourcing strategies, reported as percentage of shop owners surveyed who thought that at least half of their customers used this strategy

Strategy	Iranduba	Novo Airão	Presidente Figueiredo	Manacapuru	Manaus	%
Fruit trees at home	66	58	56	47	57	56
Fishing	82	69	9	54	11	51
Rural plots	38	66	66	32	10	41
Chickens	35	35	14	13	10	22
Hunting	14	35	3	4	6	12
Vegetables at home	14	10	5	4	3	8

found to be unrelated to access to healthy food. Reasons for this might include the very high density of small family-run shops, especially in the poorest areas. Although the range of foodstuffs available within any individual one of these shops is lower than in more sophisticated stores, the high density of these shops means that the availability of products within a local neighborhood is not necessarily compromised. Yet, shops in poorer areas were less likely to sell fruit and vegetables. This might relate to lack of demand, either due to prioritization of spending on other items or due to use of alternative sourcing of fruit from local trees by poorer households (European Food Information Council [EUFIC] 2012). Although neighborhood availability of food might be the same, food access might be better for those with higher income as their access to resources, including transport, will be greater, enabling them potentially greater options for sourcing food from a wider geographic area (Shannon 2016).

Small family-run food shops (Types 1 and 2) dominated food retail in the Amazonian urban centers studied, especially in poorer neighborhoods. Of the more sophisticated shops (Type 4; for example, with trolleys, accepting credit cards), few were in the poorest neighborhoods and instead tended to be located more strategically near commercial centers. Meanwhile, many of the poorest neighborhoods are located on the urban fringes. In poor areas, although there are less of the more sophisticated shops, there were many more shops overall. These predominantly small, family-run shops with few services might be in high demand with households depending on shopping very locally. These small shops also provide the additional advantage of providing a livelihood for an estimated one in fifty households. Unlike the context for most other food desert studies to date (Jiao et al. 2012; Frndak 2014; USDA 2015; Barnes et al. 2016), large supermarket chains are yet to dominate the food market in this transitioning economy and thus have not had the impact seen elsewhere of outcompeting local neighborhood shops (Cummins and McIntyre 2002; Gartin 2012). Our results show, however, that in areas with lower income poverty, the overall density of shops is lower, whereas the facilities offered by stores are higher. This implies that as an economy continues to transition, there is a shift toward fewer but larger food shops. The introduction of supermarkets within the United Kingdom and United States was linked with the emergence of food deserts (Cummins and Macintyre 2002; White and Hamm 2014); thus, care must be taken to ensure that as the economy transitions, the food access of less mobile households does not worsen.

Interestingly, food prices were generally found to be cheaper in poorer areas. This result is opposite to the findings of most previous studies, where the prevalence of higher priced, small convenience shops and lack of cheaper supermarkets in poor areas causes prices to be higher (Beaulac, Kristjansson, and Cummins 2009). This novel finding might be due to the very different retail food provision available within the study region. It also suggests that the market adjusts well to relative purchasing power and that poor food access is not always about market failure. Although food might overall be slightly cheaper in the poorest neighborhoods, this does not mean that it is more affordable when income differences are taken into consideration. The proportion of income required for purchasing the basket food items increases exponentially in relation to the rise in percentage of households living in absolute poverty. The average proportion of monthly household income required to purchase the basket items is greater than 80 percent in the poorest urban areas, and this basket only represents part of a household's required food intake (NEPA 2011). This implies that for some households the cost of purchasing sufficient healthy food might exceed their income, even before accounting for other essential living costs. Incomes have failed to rise in line with very high inflation (11 percent in 2015; Banco Central do Brasil 2016), meaning that affordability is currently getting worse.

Alternative Strategies

Alternative food sourcing strategies were employed by many households, consistent with other studies elsewhere in the Amazon (Parry, Barlow, and Pereira 2014). The high proportion of fruit trees at home and low numbers growing vegetables at home concur with the findings of WinklerPrins (2002). Even within the metropolis of Manaus, fruit trees at home appear to be a significant alternative food source and could be important in mitigating some of the negative food desert impacts arising from lack of retail availability. Land outside of the city and its related urban–rural transfers (WinklerPrins 2002) was also found to be important in most urban centers, although less so in Manaus, presumably due to the size of the city; yet even here in the metropolis, 10 percent of shop owners still thought that over half of their customers had land outside of the city. Although fish is rarely present within retail food provision, it appears to remain a significant alternative source of food in many urban centers across the study region. In Iranduba the proportion of households thought to fish is particularly high. Despite a nutritional transition from fish to frozen chicken (Nardoto et al. 2011), fishing was important in other smaller riverine centers (Iranduba Novo Airão and Manacapuru) but less important in Manaus and in the urban center away from a river (Presidente Figueiredo).

The extent to which different alternative sourcing strategies are employed was found to vary among urban centers. Sometimes the reasons for this variation are obvious, such as ease of access to a river affecting likelihood of fishing. Yet, in other cases (e.g., keeping chickens) further investigation is needed to discover and understand strategies specific to a given community. Overall, it is clear that alternative food sourcing strategies play a potentially significant role in supporting household food security and alleviating potential impacts of living in a food desert (as defined in terms of retail food access; Frayne, McCordic, and Shilomboleni 2014). This might be especially significant in the case of alternative provision of fruit, which is insufficiently available through retail provision in many areas (WinklerPrins 2002). The availability and consumption of nonretail sources of fruit warrant further investigation to more fully understand the extent to which this might help alleviate the impact of food deserts. When taking the impact of alternative food sourcing strategies into account, it is likely that defining food deserts based only on retail food provision will overstate the food access problem within a rainforest setting, although the impact will vary among urban centers. Elsewhere in the Global South alternative food sourcing strategies might also influence the true impact of conventionally defined food deserts on food security. The relative prevalence of these strategies is likely to be place specific, however, and thus understanding local context is very important. Interestingly, the results challenge the application and relevance of conventional food desert definitions to non-Western contexts given the high prevalence of alternative food sourcing strategies in the urban centers we studied. Incorporating alternative food sourcing into the spatial assessment of food deserts was beyond the scope of this study given the data available, but it does highlight an important area for future research.

Limitations

Further research is needed to ascertain whether nutrition and health are indeed worse within those areas identified as food deserts. Socioeconomic and spatial inequalities in nutrition and food security also need to be considered (Beaulac, Kristjansson, and Cummins 2009). The food desert concept involves making simplified assumptions about households within a given area, yet there might be significant variation in food sourcing behaviors, and households will employ different strategies for sourcing food depending on their capabilities (White and Hamm 2014). It should be recognized that not all food sourcing will take place on foot and near home and that food sourcing might vary considerably between households, according to transport availability and mobility patterns. Some households might, for example, purchase food in other localities such as near their workplace rather than in their immediate neighborhood. Mobility is much higher in some locations than others (Shannon 2016) and might also vary significantly between individuals within the same neighborhood affecting the true geographic extent within which they shop for food (Chen and Kwan 2015). The thresholds (both distance and selection of products) used will also significantly affect the spatial distribution of food deserts. For this reason they should be used for understanding inter- and intraurban variation and should not be interpreted as a definitive number of households living within a food desert.

Policy Implications

Drawing on the findings of this research, a number of policy interventions that might reduce the prevalence or food security impact of food deserts on urban households in Amazonia and other transitioning economies are highlighted. Although the food basket prices were cheaper within income-poor neighborhoods, relative to income, sufficient healthy food remained cost prohibitive for the most deprived households. Low household income presents one of the biggest challenges to the ability of households to access sufficient healthy food for a nutritious diet. In Brazil, continued efforts by the federal government to raise the incomes of the poorest members of society, through cash transfers and improved educational and employment opportunities, will therefore remain key to alleviating food deserts. Research shows that conditional cash transfer schemes such as the Family Grant (*Bolsa Família*), have positive impacts on food security, although they might also encourage consumption of higher density calories and greater obesity (Wezel and Bender 2003; Cotta and Machado 2013).

It was observed that most households shop close to home, especially for those living in poor neighborhoods located on the urban fringes where public transport is largely absent. Within the urban centers studied, public buses are unreliable and travel only along major routes, partly due to poor quality roads in deprived neighborhoods. Small privately owned minivans served as buses on some routes in Manaus and motorbike taxis existed in all study cities, yet both options remain cost prohibitive for the poorest members of society. Improvements to the level of service and affordability of public transport for poorer households might improve their mobility and subsequently, food access (Reisig and Hobbiss 2000). Hence, investments to improve infrastructure (especially roads) in poorer neighborhoods should aid mobility and attract investment in terms of food retail. Care also needs to be taken to ensure that the expansion of large housing schemes for low-income families such as "Minha Casa, Minha Vida" (My Home, My Life; CAIXA 2016) occurs in parallel with the development of local shops and services able to provide sufficient access to healthy food.

The availability of fruit and vegetables in shops was generally low in this study context. Low levels of agriculture within Amazonas state and poor transport connections both within the state and to elsewhere in Brazil (Fenley, Machado, and Fernandes 2007) are likely to limit supply, keeping prices relatively high. Investment nationally to improve transport links both within Amazonas state and to the rest of Brazil might help increase access to affordable food. New road links would be ill advised because they invariably lead to uncontrolled deforestation and thus would exacerbate global climate change (Fenley, Machado, and Fernandes 2007). At the municipal scale, policies supporting periurban agriculture might also help to increase supply of fruit and vegetables.

The results also showed that in urban Amazonia, alternative food sourcing—especially fruit trees, fishing, and home gardens or periurban farm plots—might be significant contributors to local health and nutrition. Indeed, one of the principal reasons people maintain periurban food plots is to minimize risk of food insecurity (Lerner and Eakin 2011). Therefore, as urban areas continue to grow it is important for local planning policy not to overlook the potentially important role of these alternative strategies for food security. Local urban planning should therefore seek to maintain access for urban populations to alternative food sources such as urban fruit trees and periurban food plots. In addition to improving the supply of foods such as fruit and vegetables, educational interventions to increase demand for vegetables might be beneficial. WinklerPrins (2002) observed low preference for vegetables within Amazonian towns and our observations during fieldwork appear to confirm this. This lack of preference might influence demand and thus current lack of availability. Similar barriers to fruit and vegetable consumption have been found in Europe, where fruit and vegetable consumption is affected by income and affordability, level of education and knowledge of nutritional importance, local availability, and taste preferences (EUFIC 2012).

Conclusion

In providing the first examination of food deserts in a rainforest context, this article has demonstrated that food deserts appear to be widespread in urban centers, regardless of their size. It is clear that some elements of a healthy diet, especially fruit and vegetables, are lacking in local retail provision. It is also evident that although food deserts are no more likely in poorer areas and prices are in fact generally cheapest in the poorest areas, the proportion of average household income required to purchase a healthy basket of food is unaffordable for many of the poorest households. The full extent of nonretail food provision and its influence in alleviating the impacts of food deserts warrant further investigation. The availability of fruit from trees at home or within the local neighborhood, along with continued urban–rural linkages in the form of land outside the urban extent, could play a significant role in reducing the effect of food deserts where availability of fruit and vegetables is a significant problem. Other alternative food sources such as fishing might also help to reduce challenges relating to affordability of food. As the Amazonian economy continues to transition, the future importance of alternative food sources remains to be seen. The role of alternative food sourcing strategies, especially in smaller urban centers, leads us to question the applicability of conventional food desert research—the origins of which lie in Western contexts with mature economies and high supermarket penetration—to transitioning economies. Key policy implications have been highlighted, including the need for continued programs designed to improve incomes for the poorest households and infrastructure investment to improve affordable supply of healthy foods.

The method presented here could usefully be applied in other contexts where supermarkets are not yet significant to local food retail. More research is, however, still needed to improve understanding of food deserts within transitioning economies and across the Global South, where the majority of those most vulnerable to food insecurity reside. Importantly, local food contexts (both retail and nonretail) need to be understood and explored together to effectively expand the concept of food deserts.

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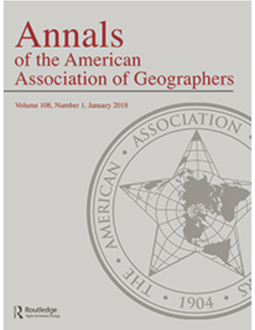
GEMMA DAVIES is the GIS Officer in Lancaster Environment Centre at Lancaster University, Lancaster LA1 4YQ, UK. E-mail: gemma.davies@lancaster.ac.uk. Her research interests include many areas of applied GIS, including food security, journey-time exposure to air pollution, and mobility.

GINA FRAUSIN is a researcher in Lancaster Environment Centre at Lancaster University, Lancaster LA1 4YQ, UK. E-mail: ginafrausin@gmail.com. Her research interests include the knowledge of plants and their uses by indigenous populations in the Amazon.

LUKE PARRY is a Lecturer in the Lancaster Environment Centre at Lancaster University LA1 4YQ, UK. E-mail: luke.parry@lancaster.ac.uk. His research interests include urbanization and linkages with environmental change and food security with a geographic focus on Amazonia.



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Social Vulnerability to Climatic Shocks Is Shaped by Urban Accessibility

Luke Parry,* Gemma Davies,† Oriana Almeida,‡ Gina Frausin,† André de Moraés,§ Sergio Rivero,¶ Naziano Filizola,# and Patricia Torres†

*Lancaster Environment Centre, Lancaster University, and Núcleo de Altos Estudos Amazônicos, Universidade Federal do Pará
†Lancaster Environment Centre, Lancaster University
‡Núcleo de Altos Estudos Amazônicos, Universidade Federal do Pará
§Independent researcher, Manaus, Brazil
¶Departamento de Econômia, Universidade Federal do Pará
#Departamento de Geografia, Universidade Federal do Amazonas

Despite growing interest in urban vulnerability to climatic change, there is no systematic understanding of why some urban centers have greater social vulnerability than others. In this article, we ask whether the social vulnerability of Amazonian cities to floods and droughts is linked to differences in their spatial accessibility. To assess the accessibility of 310 urban centers, we developed a travel network and derived measures of connectivity and geographical remoteness. We found that 914,654 people live in roadless urban centers ($n = 68$) located up to 2,820 km from their state capital. We then tested whether accessibility measures explained interurban differences in quantitative measures of social sensitivity, adaptive capacity, and an overlooked risk area, food system sensitivity. Accessibility explained marked variation in indicators of each of these dimensions and, hence, for the first time, we show an underlying spatial basis for social vulnerability. For instance, floods pose a greater disease risk in less accessible urban centers because inadequate sanitation in these places exposes inhabitants to environmental pollution and contaminated water, exacerbated by poverty and governance failures. Exploring the root causes of these spatial inequalities, we show how remote and roadless cities in Amazonia have been historically marginalized and their citizens exposed to structural violence and economic disadvantage. Paradoxically, we found that places with the highest social vulnerability have the greatest natural and cultural assets (rainforest, indigenous peoples, and protected areas). We conclude that increasing accessibility through road building would be maladaptive, exposing marginalized people to further harm and exacerbating climatic change by driving deforestation. *Key Words: Brazil, cities, extreme events, remoteness, spatial inequalities.*

尽管对城市之于气候变迁的脆弱性之兴趣日益增加，但对于为何若干城市中心较其他具有更高的社会脆弱性之问题，却未有系统性的理解。我们于本文中，质问亚马逊城市之于洪泛与旱灾的社会脆弱性，是否与其空间可及性之差异有关。为了评估三百一十座城市中心的可及性，我们发展了一个旅行网络，并衍生连结性与地理偏僻性的衡量方法。我们发现，离国家首都两千八百二十公里的距离之内，有九十一万四千人居住在没有道路的城市中心（样本数为六十八）。我们接着检验可及性测量是否解释了社会敏感度、调适能力，以及一个被忽略的风险领域——粮食系统敏感度的量化测量中的城际差异。可及性解释了上述面向个别指标的显着差异，我们从而初次展现社会脆弱性的根本空间基础。例如洪泛在可及性较差的市中心产生更大的疾病风险，因为这些地方的卫生条件并不充分，将居住者暴露在环境污染与污水之下，并因贫穷与政府失能而恶化。我们探讨这些空间不均的根本肇因，展现亚马逊偏远且无路的城市，如何在历史上受到边缘化，而其市民暴露在结构性暴力与经济劣势之下。矛盾的是，我们发现，社会脆弱性最高的地方，拥有最为丰沛的自然与文化资产（雨林、原住民族和保护地）。我们于结论中主张，透过道路建设逐渐增加可及性，将可能会适应不良，让边缘化的人们暴露在进一步的伤害中，并因驱动去森林化而使得气候变迁更为恶化。*关键词：巴西，城市，极端事件，偏远，空间不均。*

Pese al creciente interés sobre la vulnerabilidad urbana al cambio climático, no hay un entendimiento sistemático del porqué algunos centros urbanos tienen una vulnerabilidad social más alta que otros. En este artículo nos preguntamos si la vulnerabilidad social de las ciudades amazónicas a las inundaciones y a la sequía está relacionada con las diferencias en su accesibilidad espacial. Para evaluar la accesibilidad de 310 centros urbanos, desarrollamos una red de viajes y derivamos medidas de conectividad y de lejanía geográfica. Hallamos

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que 914.000 personas viven en centros urbanos sin carreteras (n D 68) que se localizan a 2.820 km de su capital estatal. Luego examinamos si las medidas de accesibilidad explicaban las diferencias interurbanas en medidas cuantitativas de sensibilidad social, capacidad de adaptación, y un área de riesgo ignorada, la sensibilidad al sistema alimentario. La accesibilidad explicó la marcada variación en los indicadores de cada una de estas dimensiones y, por lo tanto, por primera vez, mostramos una subyacente base espacial de la vulnerabilidad social. Por ejemplo, las inundaciones representan un riesgo más grande de enfermedad en los centros urbanos menos accesibles debido a que las políticas de salubridad inadecuadas en estos lugares exponen los habitantes a polución ambiental y agua contaminada, exposiciones exacerbadas por la pobreza y fallas de gobernanza. Explorando las causas raizales de estas desigualdades espaciales, mostramos cómo las ciudades de la Amazonia alejadas y sin carreteras han estado históricamente marginadas y sus habitantes expuestos a violencia estructural y desventaja económica. Paradójicamente, encontramos que los lugares que registran la más alta vulnerabilidad social tienen los más grandes activos naturales y culturales (selva pluvial, pueblos indígenas y áreas protegidas). Concluimos que incrementar la accesibilidad por medio de la construcción de carreteras resultaría ser una mala adaptación, al exponer a gente marginada a mayores males y exacerbar el cambio climático facilitando la desforestación.
Palabras clave: Brasil, ciudades, eventos extremos, lejanía, desigualdades espaciales.

In this article, we explore the role of two measures of spatial accessibility—geographical remoteness and road connectivity—in determining variation in the social vulnerability of urban centers. This piece therefore advances current understanding by first elucidating the relative accessibility of hundreds of cities in the Brazilian Amazon and then exploring how this shapes social vulnerability to climatic shocks. We assess interurban differences in social vulnerability using quantitative measures of social sensitivity, adaptive capacity, and an overlooked risk area, food system sensitivity. Finally, we engage with ongoing debates about the contentious roles of roads as either "ecologically disastrous" or pathways to development (Ibisch et al. 2016).

Social Vulnerability to Climatic Shocks

Worldwide, cities are facing climatic shocks of increasing frequency and severity, with myriad consequences for human welfare (Field 2012). This contributes to growing interest in urban vulnerability to global environmental change (Gasper, Blohm, and Ruth 2011; Pelling 2012; Tate 2013; Revi et al. 2014; Sherly et al. 2015). Consequently, understanding and reducing vulnerability to climatic shocks has advanced from academic debate to become a "political necessity" (Hinkel 2011). Understanding why some cities are more socially vulnerable than others is crucial for designing appropriate policy interventions. This is vital in the Global South, where many cities are highly vulnerable to shocks due to development and governance failures (Parnell, Simon, and Vogel 2007), compounded by overcrowding arising from rapid urbanization (Hardoy and Pandiella 2009).

Two decades of research have demonstrated that vulnerability to shocks—defined as the propensity or predisposition of people or places to be adversely affected—is multidimensional (Blaikie et al. 1994), and impacts vary according to levels of development and preexisting vulnerabilities (Birkmann 2013). Thus, hazards are not just physical events but are socially constructed situations (Cutter, Mitchell, and Scott 2000). Hence, vulnerability is generally taken as the outcome of hazard exposure and the two conventional dimensions of social vulnerability (sensitivity and adaptive capacity; Adger 2006). Extreme climatic events therefore act as threat multipliers when hazard exposure combines with social vulnerability (i.e., economic, social, and political weaknesses and stresses; Wilbanks and Kates 2010). Hazard exposure is the extent to which a place or community experiences undesirable change due to system perturbations (Turner et al. 2003).

Where societies are sensitive to shocks and lack sufficient adaptive capacity, exposure to extreme climatic events causes harm through loss of assets, reduced access to services or employment (Gasper, Blohm, and Ruth 2011), and physical and mental health impacts (Wickrama and Kaspar 2007). Sensitivity is the susceptibility to harm following exposure to a shock and adaptive capacity reflects the ability of individuals or a system to anticipate, respond to, and recover from stresses (Adger and Vincent 2005). Sensitivity reflects development stage, such as demographic transitions in fertility, population structure, and levels of education (Stephenson, Newman, and Mayhew 2010). It is affected by the impacts of previous shocks, manifested through health, nutrition, and housing conditions. Adaptive capacity is likewise strongly related to development and can be analyzed at the institutional or individual level (or aggregates thereof). This capacity represents governance, rights, and literacy (Brooks, Adger, and Kelly 2005) and is often low in developing world contexts. Deficiencies can be related to either specific (e.g., related to climate risks and agriculture) or generic capacities (e.g., limited income or political power; Lemos et al. 2016).

Vulnerability analysis tends to ignore food security (e.g., Cutter and Finch 2008; Mansur et al. 2016) even though climatic shocks can strongly affect food systems (Sherman et al. 2015). Climatic shocks can compromise food security by disrupting food access or affecting the natural resource base for local livelihoods (Maru et al. 2014). Moreover, floods and droughts can exacerbate chronic food insecurity and malnutrition in developing world contexts, especially among marginalized groups such as the urban poor (Ericksen 2008). The climate–food security literature is largely focused on food production (Ericksen 2008), yet a shock might instead disrupt the poor's access (Devereux and Berge 2000) to safe, affordable, and nutritious food by affecting income (O'Brien 2006) or transportation networks, food storage, or market dynamics (Maru et al. 2014). We therefore attempt to advance social vulnerability analysis by adding an extra dimension to Adger's (2006) framework: food system sensitivity.

Disregard of Spatial Inequalities

Studies have identified place-based differences in the level of social vulnerability to disasters with high intraregion variability (Cutter, Boruff, and Shirley 2003; Cutter and Finch 2008), including in Latin America (Hummell, Cutter, and Emrich 2016). Mapping and rankings are also widely used to describe spatial differences in vulnerability (e.g., Antwi-Agyei et al. 2012). To our knowledge, though, no study has adopted a quantitative approach to test for an underlying spatial explanation for interurban differences in social vulnerability. Overall, vulnerability science offers only limited insights into how urban vulnerability might vary spatially (see Cutter, Ash, and Emrich 2016) and even fewer as to why. This is an important shortcoming because, for example, marginalized remote rural communities are highly vulnerable to climate change (Maru et al. 2014) and this might also be true for remote urban centers. The unclear spatial basis of urban vulnerability to climatic shocks is also important because understanding difference is vital for enabling local-level climate change adaptation (Satterthwaite, Dodman, and Bicknell 2009) and humanitarian intervention during disasters. This knowledge gap is surprising given long-term recognition of spatially uneven development (i.e., inter- and intraregional disparities; N. Smith 1984; World Bank 2009). Indeed, there is widespread evidence of spatial inequalities in many of the factors that constitute sensitivity to shocks and adaptive capacity. Urban vulnerability research is dominated by case studies, though, biased toward metropolitan areas, using conflicting theoretical lenses and methodologies (Romero Lankao and Qin 2011).

Differences in accessibility to other cities could shape interurban variation in social vulnerability. Accessibility is defined as the ease with which goods and services in one location can be accessed by people living in another location (Castree, Rogers, and Kitchin 2013). Within our study context of the Brazilian Amazon, we conceptualize urban accessibility as the outcome of geographical remoteness (transport distances to other cities) and road connectivity (or not). The latter is important in contexts such as Amazonia, where urban accessibility can depend largely on fluvial transport (Salonen et al. 2012). The relationship between roads and development is contentious (Rigg 2002), and it is unclear whether roadless urban centers in Amazonia and elsewhere are more or less vulnerable to shocks than road-connected urban centers, when controlling for remoteness. Roads are also polemic because they have widespread negative impacts on ecosystems yet are mentioned in the Sustainable Development Goals for contributing to economic growth, despite the social and environmental costs (Ibisch et al. 2016).

Irrespective of whether less accessible cities are more vulnerable, spatial analysis of vulnerability should also recognize the ways in which space and spatial relations are produced (Lefebvre 1991). Ribot (2011) argued that vulnerability research must address the social and political–economic processes that have caused marginalization and vulnerability because this is a prerequisite for climate risk reduction. Accordingly, we highlight two theoretical framings of spatial inequalities that can provide insights into potential spatial variation in social vulnerability. The first engages with the work of early twentieth-century geographers and, later, geographical economists. Both groups emphasize how distance to markets determines transport costs and suggest that economic growth is lower in less accessible locations due to competitive disadvantage (Krugman 2011). The World Bank's (2009) view of spatial inequality is, not surprisingly, derived from geographical economics; less accessible cities are "lagging" in development because high transport costs and small size incur less economic growth and investment and impaired flows of finance, goods, and services. They contend that these constraints contribute to poverty and poor access to basic services such as electricity and sanitation. Yet, these arguments generally ignore the political and historical factors that strongly influence "uneven development" (N. Smith 1984).

The second framing draws on political economy, going beyond spatial patterns to examine how differences emerge and are perpetuated. Political economic geographers have analyzed the spatial nature of inequalities in well-being (e.g., N. Smith 1984; Harvey and Braun 1996; Goodchild et al. 2000) using the lenses of place-specific histories and cultures, institutions and politics, power relations, and justice (e.g., Massey 1979). Hence, this scholarship has examined spatial inequalities in development albeit not using a vulnerability framework or pursuing generalizable spatial explanations.

Study Aim and Research Questions

Here we ask whether the spatial accessibility of cities is an underlying driver of social vulnerability to extreme climatic events in the Brazilian Amazon. The vulnerability of urban Amazonians to climate change has received very little research attention (Mansur et al. 2016) and there is an urgent need for more research on the human dimensions of climatic change in this region (Brondízio et al. 2016). We address our main objective by asking four specific research questions. First, to what extent do remoteness and connectivity determine the social dimensions (social sensitivity, adaptive capacity, and food system sensitivity) of urban vulnerability to climatic shocks? Second, how are these spatial inequalities produced and perpetuated? Third, what are the relative merits of potential adaptation pathways for redressing spatial inequalities and reducing social vulnerability in less accessible urban centers? Fourth, related to the previous question, what might be the environmental and societal costs of increasing urban accessibility? We answer these questions using empirical data analysis (Q1 and Q2, see Results) and through the interpretation of our findings in relation to the literature and public policy (Q3 and Q4, see Discussion). Although explanations differ, geographical economics and political economy perspectives would agree that less accessible urban centers might suffer disadvantages that limit the capacity of individuals and institutions to thrive. Hence, we predict greater social vulnerability in less accessible urban centers due to high levels of sensitivity and low levels of adaptive capacity.

Materials and Methods

Study Region

The Brazilian Amazon is well suited to answering our research questions because many of this vast region's urban centers are located in places where accessibility is precarious (Guedes, Costa, and Brondízio 2009), dependent on a transport infrastructure highly susceptible to floods (inhibiting road transport) and droughts (inhibiting river transport; Szlafsztein 2015). These issues create challenges for municipal, state, and federal governments, tasked with reducing vulnerability and protecting citizens from harm. Moreover, Amazonian urban centers face multiple vulnerability threats: rapid urbanization (Browder and Godfrey 1997); increasing exposure to extreme floods and drought events (Marengo et al. 2013); and underdevelopment, including income poverty and low levels of education (Instituto Brasileiro de Geografia e Estatística [IBGE] 2010) and food insecurity (IBGE 2009).

Experimental Design

Our study is based mainly on analysis of secondary socioeconomic data (for dependent variables employed as indicators of social sensitivity and adaptive capacity) and spatial analysis (for independent variables) from 310 cities in the six states entirely within the Legal Amazon (Figure 1). These data sets are supplemented by primary data on food prices collected from a subset of urban centers. Our study region had 14.48 million inhabitants, 10.58 million (or 73 percent) of whom are urban, distributed in 2.70 million households (IBGE 2010). All data sources and their spatiotemporal references are described in the Supplemental Material.

Vulnerability Indicators

Accessibility Measures

We assessed urban accessibility using measures of interurban connectivity and geographical remoteness within an urban hierarchy. Our focus was place-based accessibility rather than travel time or considering individual mobility (see Kwan 2013). To assess connectivity, we developed a travel network for the study area in a

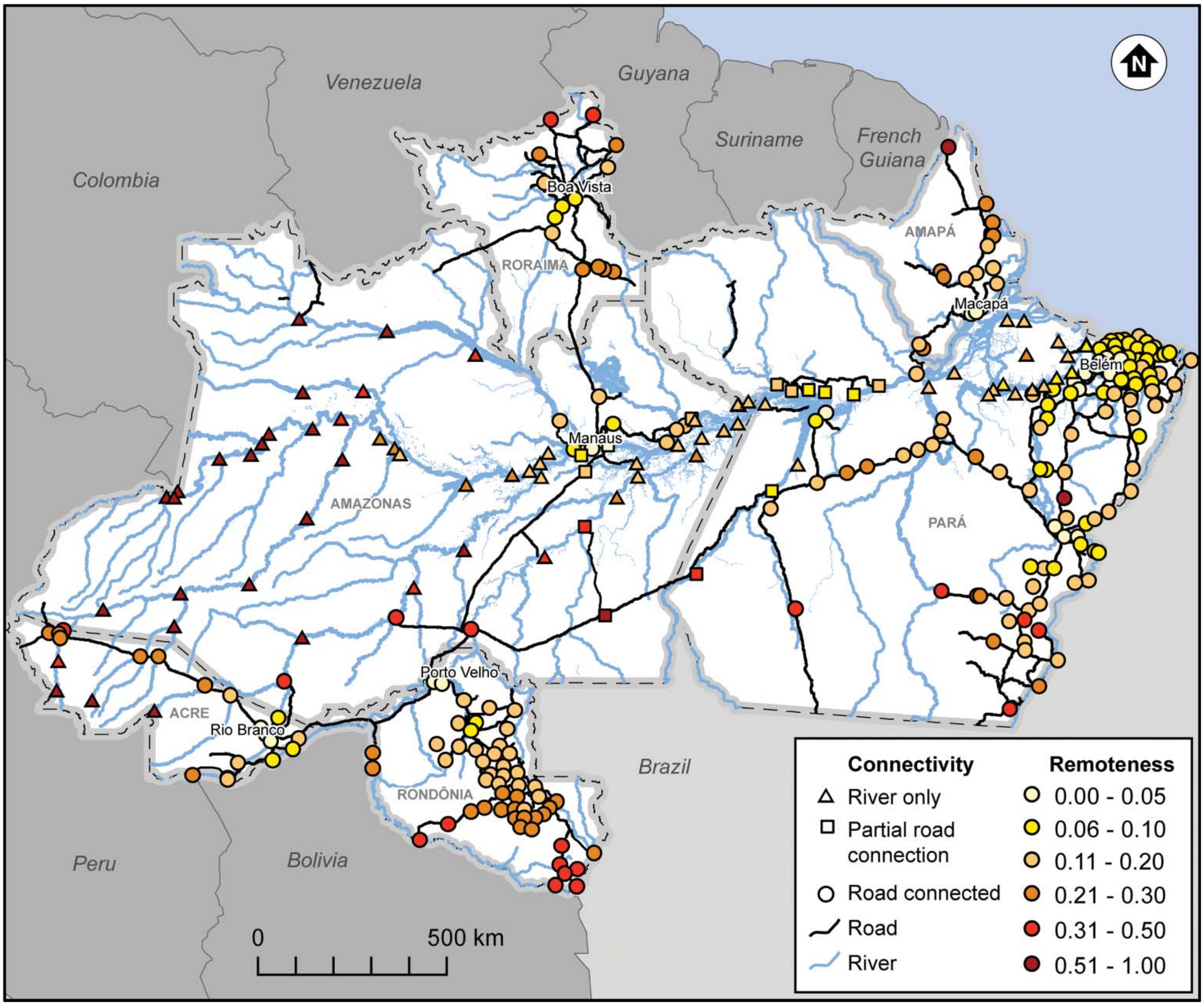

Figure 1. Map illustrating the Brazilian Amazon, road connectivity, and remoteness scores of the 310 urban centers included in this study. Also shown is the road network (official and unofficial) and river network. Shapes indicate connectivity and colors indicate the level of remoteness for each urban center. (Color figure available online.)

geographic information system (GIS), combining information on roads, river networks, and urban locations (see Supplemental Materials). We categorized each center as either (1) having no connection to the road network (roadless), (2) having access to the road network but with a route requiring partial use of rivers (ferry boats or barges to cross rivers), or (3) fully connected to the road network. We calculated a remoteness score (0.0 > 1.0) for each center, based on minimum travel distances to centers of different levels in the IBGE urban network (see Supplemental Material). Minimum travel distances between all cities were calculated by identifying routes across our network based on the likely travel potential (0/1) of an arbitrary cargo load. Distances were standardized and weighted by level (Figure 1, Figure 2, Supplemental Material; IBGE 2007), with greater weighting for remoteness from higher order cities (Supplemental Material).

Estimating Sensitivity and Adaptive Capacity

Vulnerability indicators are a well-established (and scrutinized) method for identifying vulnerable people, communities, or regions. We used a deductive approach for selecting indicators of social vulnerability to climatic shocks, drawing on theoretical links between indicators and vulnerability dimensions (Cutter, Boruff, and Shirley 2003; Tate 2012; see also Supplemental Materials). Based on consideration of theoretical linkages, our conceptualization of extreme event impacts in our study system, and data availability, we considered six elements of social sensitivity (Supplemental Material): (1) demography (Cutter, Boruff, and Shirley 2003; Revi et al. 2014; measure = young dependency ratio); (2) sanitation (Brooks, Adger, and Kelly 2005; lacking tapped water, private toilet access); (3) ethnicity (Cutter, Boruff, and

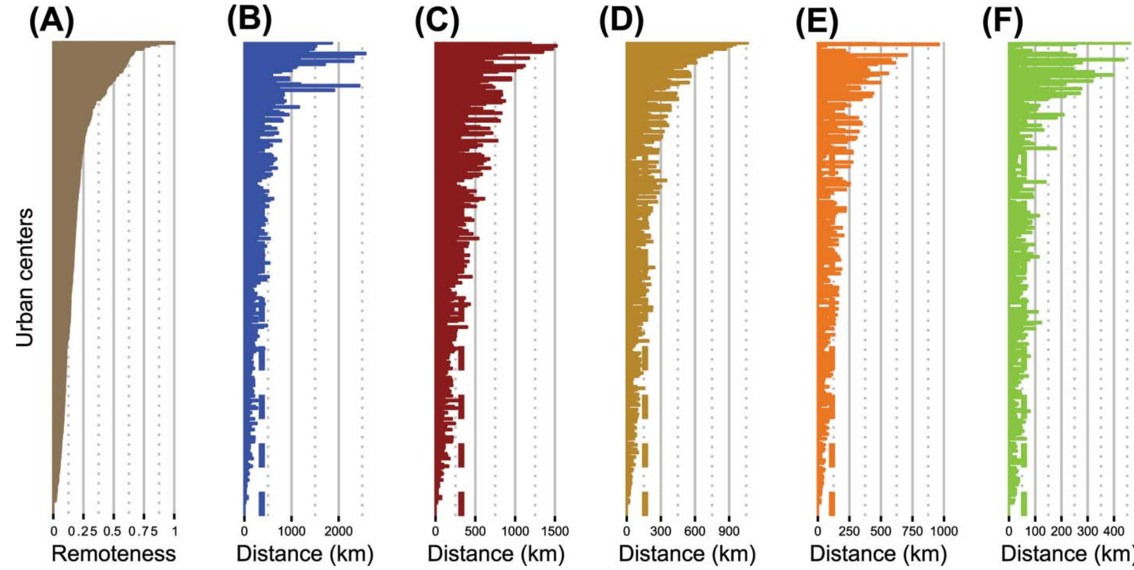

Figure 2. Travel distances from Amazonian urban centers to the nearest centers of different levels in a hierarchical urban network. Urban centers are ranked in decreasing order of overall remoteness score: (A) (gray) Based on a weighted composite of distances to (B) own regional center (blue); (C) any regional center (dark red); (D) subregional center (light brown); (E) zonal center (orange); and (F) local center (green). Journeys could be made by river or road and mean distances are displayed by colored dashed lines for each journey type. (Color figure available online.)

Shirley 2003; proportion of people who are indigenous Amerindians); (4) health (Tol and Yohe 2007; prevalence of low birth weight); (5) education (Brooks, Adger, and Kelly 2005; adults without completed elementary school); and (6) rurality (rural population).

We identified four key elements indicative of adaptive capacity: (1) health care provision (Gasper, Blohm, and Ruth 2011; our measure = prevalence of low antenatal care); (2) education provision (Cutter, Boruff, and Shirley 2003; educational delays among school-age children); (3) urban population growth (Stephenson, Newman, and Mayhew 2010); and (4) poverty (Posey 2009), including income poverty prevalence and income inequality. We normalized our indicators using minimum and maximum values and combined these into two unitless aggregate indexes (0.0 > 1.0): a social sensitivity score and an adaptive capacity deficit score.

Estimating Food System Sensitivity

Food access is strongly influenced by affordability, so we used food prices as a proxy. We collected prices for two categories of foodstuffs: those nearly always imported to Amazonian urban centers from outside the region, via major trading centers (i.e., state capitals), and foods that are generally sourced locally, through small-scale agriculture or artisanal fishing. We assessed the price of imported foods and local staples by conducting a telephone survey of hundreds of food shops across 100 urban centers in Amazonas, Pará, and Acre. Using a structured questionnaire, we recorded the cheapest price available of five imported foods (frozen chicken, tinned meat, dried spaghetti, cracker biscuits, rice) and two locally sourced foods (toasted manioc flour and the cheapest fish species available; see Supplemental Material). These foodstuffs were surveyed because of their importance within Amazonian diets (Davies, Frausin, and Parry 2017). Per capita manioc production was calculated by dividing municipal production for 2010 by the total municipal population in 2010 (see Supplemental Materials).

Statistical Analysis

Our sample size allowed us to separate the effects of urban remoteness and connectivity (which are correlated; correlation = 0.46, $p < 0.05$) and also account for unexplained spatial effects across our study region (e.g., in colonization history, climate, proximity to the rest of Brazil) using state as a fixed-effect control variable. All analyses were conducted in the R platform version 3.2.3 (R Core Development Team, Vienna, Austria). We specified generalized linear models with quasibinomial error structures for proportional outcome variables and for continuous variables with a normal distribution, linear models with Gaussian errors (see Supplemental Materials). All dependent variables

Table 1. The number of urban centers and their inhabitants related to accessibility and social vulnerability

		Road-connected			Partial			Roadless			Grand total		
SocVu	Rem	*N*	%	Population (1,000s)	*N*	%	Population (1,000s)	*N*	%	Population (1,000s)	*N*	%	Population (1,000s)
Low	Low	98	43	7,693	4	29	161	7	10	151	109	35	8,005
Low	High	42	18	575	1	7	11	2	3	70	45	15	656
High	Low	65	29	857	7	50	66	25	37	274	97	31	1,198
High	High	23	10	283	2	14	19	34	50	419	59	19	721
Total		228	100	9,408	14	100	256	68	100	915	310	100	10,579

Note: Low and high are defined as above or below the overall mean score for social vulnerability and remoteness. Also shown is the total number of urban inhabitants in each category. SocVu = social vulnerability; Rem = remoteness.

were specified in their undesirable form (e.g., proportion of households without a private toilet).

Results

Accessibility Measures

Around three quarters (228/310) of the urban centers in our study region are connected through a road network (Figure 1). These centers are home to 89 percent (9.41 million people) of the region's urban population (Table 1). We identified sixty-eight centers as having no road connection, inhabited by 9 percent (0.91 million people) of the urban population. Around half ($n = 33$) of the roadless urban centers were in Amazonas state, twenty-one in Pará, and four in Acre. Fourteen urban centers had partial connections to the road network. The most remote urban center was Itamariti, located in Amazonas state, 1,856 km travel distance from its own state capital (Supplemental Material). Roadless urban centers were significantly more remote than road-connected centers (Supplemental Material).

High Levels of Social Vulnerability in Amazonian Urban Centers

Overall, the social sensitivity and adaptive capacity deficit indicators showed that the inhabitants of urban centers in Amazonia contend with challenging development conditions that are likely to increase their risk of harm following exposure to extreme climatic events (Supplemental Material). For instance, on average over one third (36 percent) of urban households lacked access to tap water, nearly a quarter (23 percent) lacked a toilet, and nearly two thirds (64 percent) of adults lacked full elementary education.

Linkages among Social Sensitivity, Adaptive Capacity, and Accessibility

A main finding was that remote urban centers have higher levels of social vulnerability (Figure 3) because they are significantly more sensitive to shocks and have greater adaptive capacity deficits. Remoteness, connectivity, and the spatial control variable explained a relatively high amount of the variation in social vulnerability to shocks, as represented by our indexes of social sensitivity ($R^2 = 0.33$) and adaptive capacity deficit ($R^2 = 0.57$; see Table 2). Results indicate an increase of 0.50 in remoteness score is associated with a 0.07 increase in social sensitivity ($p < 0.01$; Figure 4A), and 0.12 decrease in adaptive capacity, $p < 0.001$; Figure 4C). Five social sensitivity indicators were significantly higher in remote urban

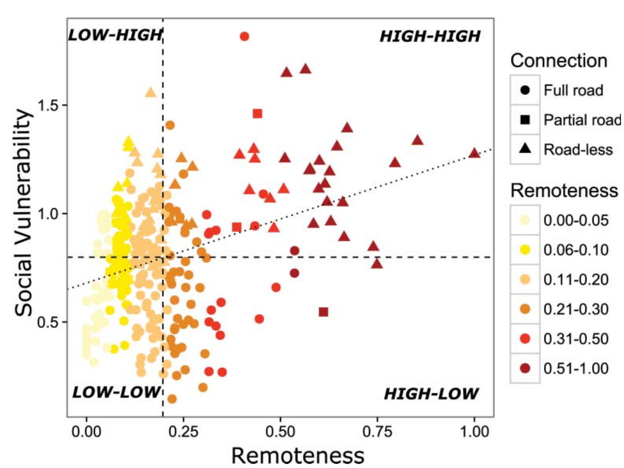

Figure 3. Relationship between remoteness and social vulnerability of urban centers in Amazonia. Social vulnerability is defined here as the sum of two dimensions of social vulnerability to shocks (social sensitivity and adaptive capacity deficit) and is illustrated in relation to two accessibility measures: connectivity (by shape) and remoteness from other cities in a hierarchical urban network (by color). (Color figure available online.)

Table 2. Results of statistical models assessing the relationships between urban accessibility and indicators of social sensitivity, adaptive capacity deficit, food system sensitivity, and environmental measures

	Remoteness					Connectivity (Roadless)				Compared to Acre	
Model	R^2	Coeff	*SE*	*t*	*p*	Coeff	*SE*	*t*	*p*	Better	Worse
Sensitivity models											
Sensitivity score	0.33	0.14	0.05	2.91	**0.0038**	0.13	0.02	6.38	**0.0000**	RO	RR
Dependency ratio	0.58	0.18	0.05	3.30	**0.0011**	0.17	0.02	7.12	**0.0000**	PA; RO	AP
No tap water	0.21	2.35	0.56	4.19	**0.0000**	−0.69	0.24	−2.86	**0.0045**	RR	PA; RO
No toilet	0.46	1.46	0.28	5.12	**0.0000**	0.31	0.12	2.57	**0.0107**	All	
Indigenous people	0.56	4.88	0.65	7.50	**0.0000**	0.98	0.50	1.98	**0.0487**		RR
Low birth weight	0.08	0.09	0.15	0.60	0.5504	0.15	0.06	2.41	**0.0164**	RO	(RR)
Low education	0.24	0.37	0.06	6.40	**0.0000**	0.06	0.02	2.41	**0.0164**	AM; AP; RR	
Rurality	0.07	0.21	0.34	0.62	0.5365	0.37	0.14	2.54	**0.0116**	AP; (AM)	
Adaptive capacity deficit models											
Adap cap deficit	0.57	0.24	0.05	4.81	**0.0000**	0.13	0.02	5.76	**0.0000**	RO; AM	
Low antenatal	0.41	0.17	0.05	3.12	**0.0020**	0.10	0.02	4.50	**0.0000**	AM; PA; RO	
Education delay	0.44	0.17	0.06	2.84	**0.0048**	0.09	0.14	3.68	**0.0003**	RO	PA
Urban growth	0.06	50.7	21.4	2.36	**0.0187**	6.27	9.21	0.68	0.4964	AM; PA; RO; RR	
Poverty	0.62	0.08	0.13	0.60	0.5464	0.34	0.05	6.36	**0.0000**	RO	PA
Inequality	0.38	0.11	0.02	5.18	**0.0000**	0.02	0.01	2.12	**0.0346**	PA; RO	RR
Food system models											
Imported food prices	0.29	0.35	0.12	2.89	**0.0050**	0.13	0.06	2.34	**0.0216**	AM; PA	
Farinha price	0.24	1.32	0.74	1.80	0.0758	−0.17	0.35	−0.49	0.6235		(PA)
Fish price	0.35	2.76	1.76	1.57	0.1214	−1.12	0.83	−1.36	0.1803	(AM)	(PA)
Manioc production	0.21	−0.22	0.62	−0.35	0.7249	−0.29	0.25	−1.16	0.2461		All
Natural capital models											
Forest remaining	0.58	3.15	0.72	4.37	**0.0000**	2.06	0.26	8.00	**0.0000**	AP; RR	PA; RO
Protected areas	0.26	2.70	0.89	3.02	**0.0027**	−0.50	0.53	−0.95	0.3454		AM; PA; (RR)
Indigenous reserves	0.37	5.04	0.69	7.28	**0.0000**	−0.17	0.36	−0.46	0.6440	RR	

Note: Roadless coefficients are compared to being road-connected. Significant state effects in relation to Acre (control group) are shown without brackets ($p < 0.05$) and with brackets ($p < 0.10$). RO = Rondonia; RR = Roraima; PA = Pará; AP = Amapá; AM = Amazonas.

centers, whereas rurality and low birth weight were not significantly different (Supplemental Material). Considering adaptive capacity deficits, four indicators were significantly higher in remote urban centers, whereas poverty prevalence was not significantly different (Supplemental Material).

Another major finding was that roadless urban centers are more sensitive to shocks (Figure 4B) and have greater adaptive capacity deficits than road-connected cities (Figure 4D). When controlling for remoteness, in roadless urban centers, social sensitivity scores are 0.13 higher ($p < 0.001$) and deficits in adaptive capacity are 0.13 higher ($p < 0.001$). All social sensitivity indicators were significantly better in road-connected urban centers (Table 2, see also Supplemental Material). Roadless urban centers were significantly worse for adaptive capacity measures, with the exception of urban population growth, which was not significantly different (Supplemental Material). For instance, in roadless urban centers, income poverty is 40 percent more likely, when controlling for other variables. State was also a significant predictor in statistical models even when controlling for accessibility measures.

The majority (61 percent) of road-connected urban centers had lower than average social vulnerability, including ninety-eight (relatively) nonremote (total population 7.7 million) and forty-two remote centers (0.57 million population; Table 1, Figure 3). Thirty-nine percent of road-connected centers had high social vulnerability, including twenty-nine nonremote (population 0.86 million) and ten remote urban centers (0.28 million population). In contrast, the majority (87 percent) of roadless urban centers had high levels of vulnerability, including twenty-five nonremote (population 0.27 million) and thirty-four remote centers (0.42 million population). Hence, only 13 percent of roadless cities had low vulnerability, including seven nonremote and two remote

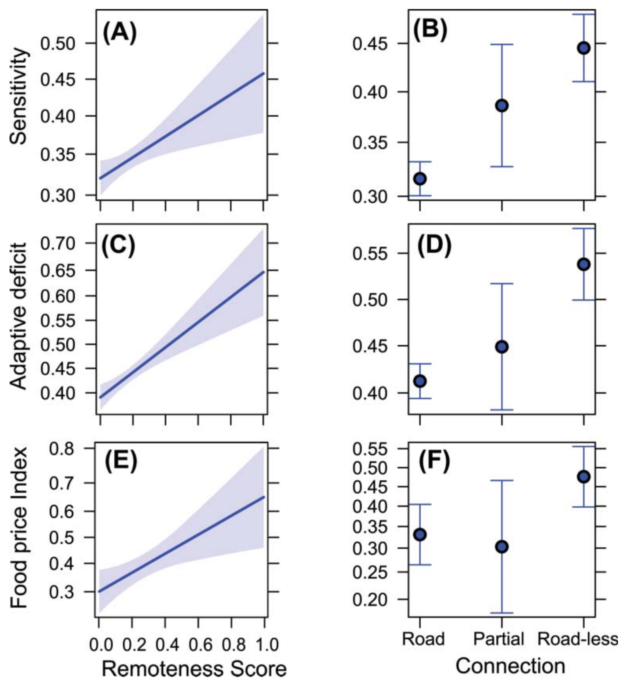

Figure 4. Relationship between urban accessibility and social vulnerability indicators. (A) Social sensitivity scores are related to remoteness from other cities ($p < 0.01$) and (B) connectivity to roads ($p < 0.001$). Adaptive capacity deficits are higher in (C) more remote cities ($p < 0.001$) and in (D) roadless cities ($p < 0.001$). A price index of five key imported foodstuffs (frozen chicken, tinned meat, spaghetti, rice, and biscuits) was significantly higher in (E) more remote cities ($p < 0.01$) and (F) in cities unconnected to the road network or dependent on crossing river(s) ($p < 0.05$). (Color figure available online.)

centers. Variation in the relationship between remoteness and social vulnerability (Figure 3), however, demonstrates that other contextual factors are also important determinants of vulnerability.

Linkages between Urban Accessibility and Food System Sensitivity

Our telephone survey revealed that imported food prices vary hugely among urban centers. For example, the per kilogram price of frozen chicken ranged from R$2.96 to R$8.00. Spatial predictors together explained 29 percent of the variation in imported food prices (Table 2). Imported food prices were significantly higher in remote urban centers—the score increased by 0.17 for a 0.50 increase in relative remoteness ($p < 0.01$; Figure 4E). Controlling for remoteness, the food price index was 0.13 higher in roadless urban centers ($p < 0.05$), compared to fully road-connected ones (Figure 4F). Road connections were not significantly related to toasted manioc flour prices. Toasted manioc flour, however, was more expensive in remote urban centers ($p < 0.10$). Fish prices and per capita manioc production were not associated with remoteness or connectivity but varied by state.

Forest Cover and Reserve Presence around Urban Centers

We found a negative relationship between urban accessibility and natural capital; there has been less deforestation around remote and roadless urban centers. Together, accessibility and the spatial control variable explained 58 percent of the variance in cumulative proportional forest loss at the municipal scale. Remaining forest cover increases significantly with remoteness, to nearly 100 percent around remote urban centers (i.e., in the surrounding rural areas of the same municipality; Table 2). Remaining forest cover is significantly lower ($p < 0.0001$) around road-connected than roadless urban centers (Figures 5A and 5B). Strictly protected areas cover a significantly higher ($p < 0.01$) proportion of remote municipalities and are more prevalent around urban centers with partial road connections than either full- or roadless urban centers (Figures 5C and 5D). Coverage of indigenous reserves was not significantly related to road connectivity but was strongly related to the remoteness of urban centers. Indigenous reserves coverage was very low around nonremote urban centers and very high (in many cases over 50 percent of land area) around highly remote urban centers (Figure 5E and 5F).

Discussion

Our findings provide clear evidence that less accessible urban centers in Amazonia have greater social vulnerability, indicating higher potential impacts of extreme climatic events. Striking interurban differences in social sensitivity to shocks, adaptive capacity, and food system sensitivity were partly explained by two spatial factors: remoteness from other urban centers and road connectivity. This study therefore demonstrates an underlying spatial dimension of the vulnerability framework (Adger 2006), with significant application for refining vulnerability assessment. Our results show that marginalization affects not just subgroups of people (Young 2009) but also less accessible places. We scrutinize whether urban accessibility is a root cause of vulnerability (Blaikie et al. 1994) using two framings for explaining spatial

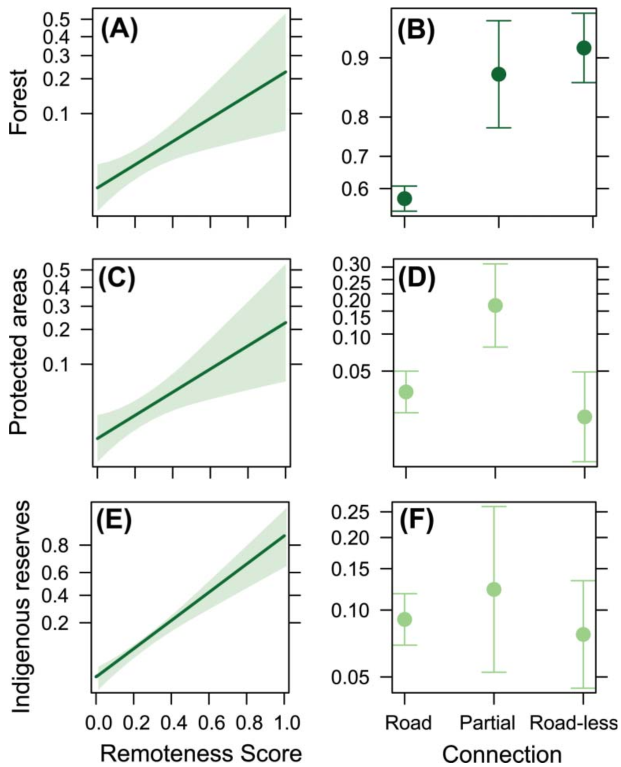

Figure 5. High natural capital and reserve coverage around less accessible cities. The proportion of original forest remaining (i.e., inverse of deforestation extent) is higher around cities that are (A) remote ($p < 0.001$) and (B) unconnected to the Amazonian road network ($p < 0.001$). Remoteness is associated with higher proportional coverage of (C) protected areas ($p < 0.01$) and (E) indigenous reserves ($p < 0.001$). The coverage of (D) protected areas and (F) indigenous reserves is not significantly different around roadless and road-connected urban centers. (Color figure available online.)

inequalities (Rigg et al. 2009): geographical economics and political economy. As we attempt to illustrate, higher social vulnerability to climatic shocks is related to economic and political history (Ribot 2011). We also reflect on the context-specific relationship between accessibility and urban vulnerability and explore adaptation pathways for reducing spatial inequalities.

This article builds on research showing high vulnerability to climate change in remote rural communities (Maru et al. 2014) and shows that this also applies to remote urban centers. Our study also contributes to a small but growing literature on the human dimensions of climatic change in Amazonia (Pinho, Marengo, and Smith 2015; Sherman et al. 2015; Brondízio et al. 2016; Mansur et al. 2016). It is significant that following decades of deforestation, road building, and colonization in Amazonia, four fifths of urban centers are at least partly connected to the road network, and these urban centers are home to nine out of ten city dwellers. In this urbanized forest "wilderness" (Parry, Barlow, and Pereira 2014) it is paradoxical (to environmentalists; Raudsepp-Hearne et al. 2010) that we found places with the greatest natural capital to have the greatest social vulnerability. We highlight the social and environmental risks posed by road building (Ibisch et al. 2016) and consider the relevance of our findings for other systems.

Less Accessible Cities Are More Sensitive to Climatic Shocks

Our study shows that inhabitants of remote and roadless urban centers are more susceptible to harm following exposure to climate shocks, reflective of an earlier stage of development and demographic transition (Stephenson, Newman, and Mayhew 2010). In other words, a given flood or drought would be more harmful to the inhabitants of less accessible cities, even if exposure was uniform. We show how spatially unequal vulnerability to climatic shocks is partly the outcome of variable access to sanitation among urban centers. Poor sanitation reflects inadequate public infrastructure and poor housing conditions related to poverty and deprivation (Perz 2000). It also exposes people to health risks from environmental pollution and contaminated water supplies (Brooks, Adger, and Kelly 2005). The health impacts of extreme events in Amazonia are poorly understood, but reports suggest outbreaks of diseases during floods (e.g., hepatitis and rotaviruses) and restricted access to safe drinking water, food, and energy during droughts (Supplemental Material). The "racial" aspect of vulnerability relates to lack of access to resources, cultural differences, and marginalization (Cutter, Boruff, and Shirley 2003). Consistent with case studies of remote, vulnerable communities (Maru et al. 2014), indigenous people made up a greater proportion of the urban population in less accessible urban centers.

Strikingly, low birth weight was significantly more likely in roadless municipalities, even when controlling for remoteness. This indicates lower levels of maternal health and nutrition (Christian 2010) and food insecurity (Rose-Jacobs et al. 2008) in these places and supports a posited link between "roadlessness" and malnutrition (Ibisch et al. 2016). Chronic food insecurity and malnutrition in roadless urban centers in the Global South might arise from a combination of stressors, including dietary intake, unemployment and housing conditions (Borders et al. 2007), the burden of insect-borne and parasitic diseases (Steketee 2003), and perhaps impacts of previous climatic shocks. We found evidence of limited education among adults in less accessible urban centers, further supporting Ibisch et al.'s (2016) predictions. Low education suggests the populations of less accessible urban centers are more susceptible to harm when exposed to shocks (Brooks, Adger, and Kelly 2005), due to increased likelihood of low salaries, informal employment, access to information, and limited power. Limited education in these Amazonian centers might reflect either relatively recent waves of rural–urban migration and poor rural education provision (Parry et al. 2010) or shortcomings in urban education provision. Many aspects of the potential harm experienced by the inhabitants of less accessible urban centers are evidence of societal marginalization (cf. Ribot 2011).

Less Accessible Urban Centers Have Lower Adaptive Capacity

Adaptive capacity was lower in less accessible centers, meaning that the ability of their residents and institutions to anticipate, respond, and recover from stresses is limited (Adger and Vincent 2005). Good antenatal care is vital for reducing maternal mortality and was worse in these places. This implies that local health services would be unable to effectively respond to extraordinary demands, such as disease outbreaks during extreme climatic events (Hales, Edwards, and Kovats 2003). Low uptake of antenatal care in developing world contexts is linked to low availability of clinics and perceived low quality of care (Say and Raine 2007) and consistent with evidence of spatial inequalities in health care (Gatrell and Elliot 2014). Significant educational-stage delays among teenagers in less accessible municipalities might reflect weak school provision, with teacher absence or school closures, for example. Educational delays also illustrate the "blurred" distinction (Hinkel 2011) between adaptive capacity and sensitivity because household deprivation also influences school attendance and attainment (Engle and Black 2008).

Population growth was faster in remote towns yet not significantly different in roadless towns, even though both forms of (relative) inaccessibility were associated with high dependency ratios. Perhaps poor roadless towns experience relatively high rates of out-migration to larger urban centers (Garcia, Soares-Filho, and Sawyer 2007) and thus the linkage between fertility and population growth is partially broken. Rapid population growth compromises adaptive capacity by overloading public services such as water, sanitation, and health systems and causes unemployment (Stephenson, Newman, and Mayhew 2010; Gasper, Blohm, and Ruth 2011). There is a two-way interaction between poor public service provision and under-development in Amazonia because limited local economic activity limits local investments in services and infrastructure, which reduces employment opportunities (Brondízio 2011). Moreover, embezzlement of public funds by mayors and associates is rife in remote Amazonian towns, partly due to limited state capacity for financial scrutiny in these places (Jardim 2016).

Our findings suggest that weak public administration combines with inequality and deprivation in remote and roadless urban centers to confer intergenerational disadvantages and high social vulnerability to shocks. This mirrors research in Australia showing that people living in remote rural communities encounter economic and social disadvantages throughout their life course (Tanton, Gong, and Harding 2012). Accessibility explained considerable variation in vulnerability, yet significant deviations from this trend highlight a tension in the utility of identifying generalizable determinants of vulnerability. It is clear that it is also important to understand contextual place-specific differences (Romero Lankao and Qin 2011) as well as develop measures of social vulnerability that are meaningful to local people (Oulahen et al. 2015).

Higher Food Prices in Less Accessible Urban Centers

Urban accessibility is linked to the sensitivity of food systems because chronic high food prices in remote and roadless places make lower income groups more vulnerable to price shocks. The prices of staple foodstuffs normally imported to Amazonia via regional centers are more than twice as expensive in the most remote centers compared to the least remote and significantly more expensive in roadless urban centers. Hence, even during nondrought periods the affordability of these staple foods is lower in less accessible places. Consequently, if price increases occurred in remote and roadless centers due to droughts, the poor would face greater risks of disrupted food access (Devereux and Berge 2000; Maru et al. 2014). Indeed, if adjusting incomes by food prices (Shorrocks and Wan 2005), income poverty would also be higher in remote and roadless urban centers. Our results tentatively support the hitherto untested assumptions that distance from markets is indicative of vulnerability to food insecurity (Haan, Farmer, and Wheeler 2001). Our findings are also consistent with research in the Solomon Islands that found that overall remoteness contributed to national vulnerability because high transport costs between urban centers drove up the prices of imported foodstuffs (Schwarz et al. 2011). Linkages between accessibility and the price of locally produced foods were less apparent. In summary, our results of food prices and birth weight support findings that the impacts of climate shocks on food insecurity and malnutrition are unequally distributed (Grace, Brown, and McNally 2014).

Urban Vulnerability in Amazonia

Research into climatic change in Amazonia is dominated by environmental concerns (e.g., Davidson et al. 2012), and understanding of local health and social impacts is sorely lacking (Brondízio et al. 2016). This bias does an injustice to the ~25 million inhabitants of Amazonia, who are increasingly exposed to extreme hydroclimatic events (Marengo et al. 2013; Filizola et al. 2014). Our study therefore makes an important contribution to current knowledge, especially in relation to cities. Overall, we found high levels of social vulnerability for Amazonian urban centers. This is congruent with a recent Brazil-wide vulnerability assessment (Hummell, Cutter, and Emrich 2016), although our analysis controls for the potential biases of using only municipal-scale aggregate data that homogenize differences in rural and urban social vulnerability (Cutter, Ash, and Emrich 2016). This is important because the ways in which urban Amazonians cope (or not) with flood and drought events are likely to be qualitatively different from the strategies and capacities of rural communities (Pinho, Marengo, and Smith 2015; Sherman et al. 2015). Our central findings are also supported by a case study of Eirunepé, a town with poor public service provision, rendered "invisible" to outsiders by its remoteness (Schor 2013). Other smaller scale urban studies in the Brazilian Amazon have also found ongoing deficiencies in infrastructure, public services, and employment opportunities (Costa and Brondízio 2011). Moreover, Mansur et al. (2016) found that within urban centers, the marginalized poor tend to live in the areas most prone to flooding, combined with low levels of sanitation. Spatial inequalities with richer regions in Brazil are persistent because two decades ago Browder and Godfrey (1997) observed that rapid population growth in Brazil's "rainforest cities" had not been accompanied by sufficient economic growth or local development, resulting in "overurbanization" (see Supplemental Materials). Urban expansion in the 1980s entailed rapid shantytown growth, pollution, poor access to social and medical services, and inadequate provision of basic services such as water and sanitation (Perz 2000; Guedes, Costa, and Brondízio 2009).

Underlying Drivers of Spatial Inequalities

Our quantitative findings provide insights into the consequences of accessibility for social vulnerability to climatic shocks but they cannot explain why remote and roadless urban centers are underdeveloped. We interpret our results using the positivist explanations posited by geographical economists versus the more critical, Marxist-influenced arguments of political economy. The importance of transport costs in economic geography (Hoover 1948) could partially explain high food prices in remote Amazonian urban centers. "New" geographical economists argued that proximity to major centers also promotes higher economic growth due to greater flows (of information, ideas, and technology; Krugman 1999) and agglomeration economies in which larger markets grow faster (Krugman 2011). Using this lens, southern Brazil is a more attractive place to produce than the north because of concentrated purchasing power and intermediate input availability (Krugman 1999). These factors have sustained market and supplier concentration and might also partly explain relatively low social vulnerability to hazards in southern Brazil (Hummell, Cutter, and Emrich 2016). The World Bank (2009) certainly follows a core–periphery doctrine and regards spatial inequalities in economic growth between well-connected "leading" areas and less accessible "lagging" areas as inevitable. Gallup, Sachs, and Mellinger (1999) suggested that "hinterland regions" are geographically disadvantaged and exhibit inhibited development due to high transport costs. Applied to our results, high social vulnerability in less accessible urban centers is related to underdevelopment, a consequence of high transport costs impeding flows of goods (ranging from imported food items to exported natural resources or agricultural produce), information, and ideas. Critical and radical geographers, however, have long criticized the reduction of space to an economic variable (Bunker 1989). Using absolute notions of space, they argue, ignores the role of politics, power, and history in producing space and spatial relations (following Lefebvre 1991). Hence, assumptions that spatial inequalities are inevitable or even desirable (Hirschman 1958) are rejected.

Understanding the underlying causes of marginalization and vulnerability is an important prerequisite of any climate risk reduction approach (Ribot 2011). Vulnerability and resilience research, however, can offer little guidance on how spatial inequalities emerge and has been criticized for ignoring, power, history, and social relations (Brown 2016; but see Romero Lankao and Qin 2011). In contrast, political economists have explored the role of history and power structures in producing unequal regional development (Massey 1979; N. Smith 1984; Martin 1999), and their insights provide useful heuristic tools for interpreting spatially uneven social vulnerability. Political economic explanations for spatial inequalities in development rest on Lefebvre's (1968) contention that space is always political, reflects social facts, and influences social relations. Moreover, political economists argue that, left unchecked, capitalism inevitably leads to uneven regional development. In that sense, spatial inequality in Amazonia is unsurprising because urbanization in developing countries has been characterized by inequality between rural and urban, between urban centers and within urban centers (D. A. Smith 1996). We argue that the underlying explanation for higher social vulnerability in less accessible urban centers is that politics and history—both inextricable from capitalist penetration of Amazonia (Browder and Godfrey 1997)—have shaped the urban hierarchy and created "spatially uneven institutional geographies" (Amin and Thrift 1995). For example, highways in Amazonia have been strategically placed to facilitate resource extraction, agricultural expansion, and international trade. The Amazonian urban hierarchy has also been profoundly influenced by the politics of migration, colonization, state creation, and regional identities (Browder and Godfrey 1997).

To understand the causal mechanisms leading to underdevelopment in less accessible urban centers, we point to Young (2009). She reasoned that structural inequalities are unjust and result from five forms of oppression; exploitation, marginalization, powerlessness, cultural domination, and violence. Young addressed inequalities among social groups, and we extend this to explore how oppression might have created spatial inequalities in social vulnerability. Clearly, the economic history of Amazonia has been defined by the exploitation of natural resources and labor to meet global demand for commodities. The rubber boom led to the diffusion of poor migrants across Amazonia and was characterized by exploitation of workers and direct or indirect violence against indigenous peoples (Dean 1987; Guzmán 2013). Notably, rubber wealth accumulated in large trading centers rather than in provincial outputs. Applying Massey's (1979) analysis to contemporary Amazonia, the labor demands of Manaus's industrial district could mean that underdevelopment in provincial cities suits the demands of capital interests because it promotes a flow of cheap labor. Marginalization of remote and roadless urban centers also reflects political centrism—the concentration of power and capital in capital cities (Massey, Amin, and Thrift 2003). Historical analysis shows that remote places become marginalized and underdeveloped due to distance from centers of power, which systematically exclude certain social and ethnic groups (Kanbur and Venables 2005; Rigg et al. 2009). Importantly, certain interests benefit from regional inequality and its perpetuation, and these interests are overrepresented in the political and economic institutions reproducing these inequalities (Rigg et al. 2009). Cultural domination of indigenous people arises from unequal power relations and colonial history (Richmond and Ross 2009), which is itself linked to capitalist penetration. Our results show that indigenous people are more populous in the marginalized, less accessible urban centers. We also show how social vulnerability predisposes the citizens of relatively inaccessible urban centers to harm from extreme events, through violence that is structural (Baker 2010) and "silent" (food insecurity and malnutrition; Watts 1983).

Policy Options for Reducing Social Vulnerability in Amazonia

Would transport infrastructure improvements benefit vulnerable people living in less accessible urban centers? According to the World Bank (2009), investing in transport infrastructure in the Global South can reduce distances between cities and encourages increased economic growth. Geographical economists have also argued that development in "hinterlands" is constrained by transport costs and recommended investment in related infrastructure (Henderson 1999). Although causality is unclear, improved transport infrastructure has been associated with economic growth (Calderón and Servén 2014) and might lead to a decline in the primacy of large cities. Proponents believe that these investments stimulate growth and reduce poverty by lowering transport costs and boosting productivity, wages, information flows, and labor mobility (e.g., Reardon, Stamoulis, and Pingali 2007). However, urban agglomerations might continue to thrive even if initial locational advantages are eroded by new transport infrastructure (Venables 1999). Furthermore, a political economy lens suggests that making roadless urban centers connected would affect social groups unequally and reinforce existing vulnerabilities. In Southeast Asia, connecting remote communities with roads has been motivated by quelling insurgency and market integration, the latter having mixed economic effects (Rigg 2002).

The social risks posed by building roads in Amazonia are supported by evidence that they become focal points for violent social conflict (Dalakoglou and Harvey 2012), marginalization of vulnerable social groups, and disease outbreaks (Barcellos et al. 2010; Ibisch et al. 2016). Moreover, road building in Amazonia would be maladaptive because the inevitable deforestation and land use change would contribute to further climate change (Ibisch et al. 2016), outweighing the potential benefits to some inhabitants of a given city (Eriksen et al. 2011). Indeed, new roads could undermine the “resourcefulness” of remote places (Maru et al. 2014) if deforestation reduced access to diversified livelihoods and natural resource use and inmigration compromised existing social relations. Nevertheless, the persistence of forest poverty to privilege a conservationist agenda and mitigate climate change is unjust (Brown 2016). River dependency is problematic for roadless urban centers in Amazonia during drought periods and warrants investment in adaptation (Maru et al. 2014). Alternative, more climate-friendly strategies for maintaining accessibility during droughts include hovercraft transport (Kubo, Akimoto, and Moriwake 2003) or improved air transport infrastructure (e.g., more hydroplanes). The impacts of transport problems could also be reduced by moving toward a more local food system (Sundkvist, Milestad, and Jansson 2005).

If resilience is the antonym of vulnerability, then building the former is critical to reducing the latter (United Nations Development Program 2014). Brown (2016) argued that building resilience can be radical—escaping assumptions of economic growth—through “positive transformations” that redress structural inequalities. After all, balanced economic growth is not the only means of redressing spatial inequalities and injustice. Accounting for historical wrongs is also a legitimate criterion for making spatially targeted policy choices (Rigg et al. 2009). Yet, identifying suitable pathways is challenging because actions must address the root causes of spatial inequalities in welfare and facilitate adaptation to a changing climate. Resilient development requires communities, neighborhoods, and urban centers to enhance their adaptive capacity for absorbing change, plus diversity, adaptive governance, learning, and self-organization (Nelson, Adger, and Brown 2007; Hardoy and Pandiella 2009). Adaptations must achieve transparent government (Leichenko 2011) and give voice and representation to vulnerable populations (Fransen et al. 2013). Those from marginalized places and social groups must be involved in the decision-making processes that set policy agendas. This would enable interventions to account for local priorities for livelihoods (Bunce, Brown, and Rosendo 2010) and thus engage with the place-based nature of vulnerability (Cutter, Boruff, and Shirley 2003). The Brazilian government has invested in policies likely to assist the poor and vulnerable with adaptation, including health promotion and cash transfers (Lemos et al. 2016). Key services, however, such as education, sanitation, and health care, are worse in less accessible places, evidence of distributive injustice. Further challenges in the Brazilian Amazon include deficiencies in tax collection (Costa and Brondízio 2011), a lack of public early warning systems (Pinho, Marengo, and Smith 2015), and a poorly funded natural disasters agency that overlooks long-term adaptation (Szlafsztein 2015).

Study Limitations

Establishing linkages between indicators of social vulnerability and urban accessibility is an important first step in elucidating spatial inequalities in the potential impacts of climatic change, but important questions remain. Our indicators-based approach cannot account for how agency and subjective perceptions of shocks influence the capacity of individuals and groups to cope with environmental change (Romero Lankao and Qin 2011). Hence, we might overestimate vulnerability in less accessible urban centers by failing to account for structural adaptations to climate shocks—in transport, early warning systems, or livelihoods—that enhance coping capacity (Hardoy and Pandiella 2009). People living in remote places might have rich local ecological knowledge, cultures of reciprocity and sharing, a strong sense of place and belonging, and informal institutions that help them deal with uncertainty (M. S. Smith and Huigen 2009; Maru et al. 2014; Sherman et al. 2015). In addition, we assess only place accessibility (assuming shorter travel distances mean greater accessibility) and ignore space–time constraints mediated through, for example, mobilities related to the effects of social difference (Kwan 2013). Finally, it is important to establish whether a relationship between accessibility and social vulnerability exists in other systems. Relatively inaccessible cities are found in the Congo Basin, Mekong Delta, Sahara, Himalayas, and Arctic, all of which are increasingly exposed to climatic change (Field 2012).

Conclusions

The unique contribution of this article is using novel empirical evidence to show an underlying spatial basis for the social vulnerability of cities to climatic shocks. This was achieved by evaluating the geographic remoteness and road connectivity of hundreds of urban centers in the Brazilian Amazon and testing the role of these accessibility measures as determinants of social sensitivity, adaptive capacity, and the novel component of food system sensitivity. Understanding vulnerability to extreme climatic events is essential for developing policies that protect vulnerable places and people from harm (Field 2012). Despite clear evidence of widespread spatial inequalities in development and growing interest in the vulnerability of urban populations to environmental change, until now we have lacked a systematic framework for understanding how and why some urban centers have greater social vulnerability than others. Our results show that higher sensitivity to floods and droughts in remote and roadless Amazonian urban centers is related to underdevelopment, including poor sanitation, which increases disease risk. Furthermore, limited adaptive capacity in less accessible urban centers reflects deficient public administration and deprivation, constraining the ability to respond to and recover from shocks. Hence, we demonstrate an underlying spatial basis for vulnerability, which advances Adger's (2006) framework and Cutter's (2003) place-based analysis. Vulnerability assessments of multiple places at a community scale (Cinner et al. 2013) or county scale (Cutter and Finch 2008) have not attempted to systematically explain spatial patterns of vulnerability.

We have explored how the underlying causes of high social vulnerability in less accessible urban centers are rooted in political and economic history (N. Smith 1984; Ribot 2011), which has led to structural economic disadvantage through high transport costs (Krugman 1999) and underdevelopment. Adaptation pathways for reducing vulnerability in less accessible urban centers should build adaptive capacity through transparent and inclusive governance that accounts for historical injustices and context specificity. In contrast, even if building new roads brought certain advantages such as improved educational access, these might well be outweighed by the social costs borne by already marginalized people (Ibisch et al. 2016). New roads could also reinforce existing vulnerabilities by fueling conflict and disease and eroding social relations in less accessible urban centers. Moreover, the poorest of Amazonia's urban poor often depend on rural livelihoods (Parry, Barlow, and Pereira 2014), which could be undermined by the inevitable deforestation from new roads, which can be "ecologically disastrous" (Ibisch et al. 2016). Deforestation would also increase overall hazard exposure to climatic shocks by contributing to global climate change.

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Supplemental Materials

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LUKE PARRY is a Lecturer in the Lancaster Environment Centre (LEC) at Lancaster University, Lancaster LA1 4YQ, UK. E-mail: luke.parry@lancaster.ac.uk. He is a member of the Political Ecology group at LEC and his research interests include urbanization and linkages with environmental change and food and nutrition insecurity, with a geographical focus on Amazonia.

GEMMA DAVIES is the GIS Officer at the Lancaster Environment Centre at Lancaster University, Lancaster LA1 4YQ, UK. E-mail: gemma.davies@lancaster.ac.uk. Her research interests include many areas of applied GIS, including food security, journey-time exposure to air pollution, and mobility.

ORIANA ALMEIDA is an Associate Professor in the Nucleus of Advanced Amazonian Studies at the Federal University of Pará, Belém, Brazil. E-mail: oriana@ufpa.br. Her research interests relate to natural resource use in Amazonia, especially in relation to climatic and social change.

GINA FRAUSIN is a researcher at the Lancaster Environment Centre at Lancaster University, Lancaster LA1 4YQ, UK. E-mail: ginafrausin@gmail.com. Her research interests include the knowledge of plants and their uses by indigenous populations in the Amazon.

ANDRÉ DE MORAÉS is an independent researcher and has a long-standing affiliation with the Geography Department at the Federal University of Amazonas, 3655 - Coroado, Manaus - AM, Brazil. E-mail: and.moraes@gmail.com. His research interests relate to food access in and around roadless Amazonian cities.

SERGIO RIVERO is a Professor of Environmental Economics in the Economics Department at the Federal University of Pará, 111 - Guamá, Belém - PA, 66073-040, Brazil. E-mail: rivero@ufpa.br. His research interests relate to the human dimensions of environmental change in Amazonia, including deforestation, climate change, and natural resource use.

NAZIANO FILIZOLA is an Associate Professor in the Geography Department at the Federal University of Amazonas, 3655 - Coroado, Manaus - AM, Brazil. E-mail: nazianofilizola@ufam.edu.br. His research interests relate to hydrology and geomorphology with a particular interest in extreme hydroclimatic events and a geographic focus on Amazonia.

PATRICIA TORRES is an affiliated researcher at the Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK. E-mail: patriciactorres@gmail.com. She has previously undertaken research at the University of Sao Paulo and the Federal University of Pará, Belém, Brazil. Her research interests include biodiversity conservation and food and nutrition security in Amazonia, linked through the harvest and consumption of wild meat.

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Gemma Davies, John Dixon, Colin G. Tredoux, J. Duncan Whyatt, Jonny J. Huck, Brendan Sturgeon, Bree T. Hocking, Neil Jarman & Dominic Bryan

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Networks of (Dis)connection: Mobility Practices, Tertiary Streets, and Sectarian Divisions in North Belfast

Gemma Davies,[*] John Dixon,[†] Colin G. Tredoux,[‡] J. Duncan Whyatt,[*] Jonny J. Huck,[§] Brendan Sturgeon,[#] Bree T. Hocking,[†] Neil Jarman,[#] and Dominic Bryan[**]

[*]*Lancaster Environment Centre, Lancaster University*
[†]*School of Psychology, Open University*
[‡]*Department of Psychology, University of Cape Town, and CLLE, Université de Toulouse, CNRS*
[§]*Department of Geography, University of Manchester*
[#]*Institute for Conflict Research*
[**]*Institute of Irish Studies, Queen's University Belfast*

Long-standing tensions between Protestant and Catholic communities in Northern Ireland have led to high levels of segregation. This article explores the spaces within which residents of north Belfast move within everyday life and the extent to which these are influenced by segregation. We focus in particular on the role that interconnecting tertiary streets have on patterns of mobility. We adapt Grannis's (1998) concept to define T-communities from sets of interconnecting tertiary streets within north Belfast. These are combined with more than 6,000 Global Positioning System (GPS) tracks collected from local residents to assess the amount of time spent within different spaces. Spaces are divided into areas of residents' own community affiliations (in-group), areas not clearly associated with either community (mixed), or areas of opposing community affiliation (out-group). We further differentiate space as being either within a T-community or along a section of main road. Our work extends research on T-communities by expanding their role beyond exploring residential preference, to explore, instead, networks of (dis)connection through which social divisions are expressed via everyday mobility practices. We conclude that residents are significantly less likely to move within mixed and out-group areas and that this is especially true within T-communities. It is also evident that residents are more likely to travel along out-group sections of a main road if they are in a vehicle and that women show no greater likelihood than men to move within out-group space. Evidence from GPS tracks also provides insights into some areas where mixing appears to occur. *Key Words: GIS, Northern Ireland, postconflict, segregation, T-communities.*

北爱尔兰基督新教与天主教之间的长期冲突导致高度的隔离。本研究探讨北爱尔法斯特居民每日生活中的活动空间, 以及这些空间受到隔离影响的程度。我们特别聚焦相互连结的第三级街道在移动模式上的角色。我们改编格兰尼斯（1998）的概念, 从北贝尔法斯特中一系列互相连结的第三级街道中定义T社群, 并结合搜集自地方居民超过六千个的全球定位系统（GPS）追踪, 评估在不同空间中花费的时间。空间分隔成居民自身社群联系（群体内部）的地区、并非与任一社群清楚联系的地区（混合）, 或是对立的社群联系之地区（群体外部）。我们进一步将空间区分为在T社群内部或是沿着主要道路的路段。我们的研究通过将T社群的角色扩张至探讨居住偏好之外, 改为探讨社会分野通过每日移动行为展现的（不）连结网络, 延伸T社群的研究。我们于结论中主张, 居民明显较少在混合地区与群体外部的地区活动, 尤其对T社群而言更是如此。证据同时显示, 居民若乘坐交通工具, 则更可能沿着主要道路的群体外部部分进行移动, 且女性并非较男性而言更可能在群体外部空间中移动。全球定位系统追踪的证据, 同时对混合可能发生的若干地区提出洞见。*关键词：地理信息系统, 北爱尔兰, 后冲突, 隔离, T社群。*

Las viejas tensiones que reinan entre las comunidades protestantes y católicas de Irlanda del Norte han conducido a altos niveles de segregación. Este artículo explora los espacios dentro de los cuales se mueven los residentes del norte de Belfast en su vida cotidiana y el grado con el que estos son influidos por la

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segregación. Nos concentramos en particular en el papel que cumplen las calles terciarias en los patrones de movilidad de la gente. Adaptamos el concepto de Grannis (1998) para definir las comunidades T a partir de conjuntos de interconexión de calles terciarias dentro del note de Belfast. Estos a la vez se combinan con más de 6000 rastros del Sistema de Posicionamiento Global (GPS) tomados de residentes locales para evaluar el tiempo empleado por ellos dentro de diferentes espacios. Los espacios se dividen en áreas de afiliaciones de la propia comunidad de los residentes (dentro del grupo), áreas que no están claramente asociadas con cualquier comunidad (mezcladas), o áreas de afiliaciones comunitarias contrarias (fuera del grupo). Adicionalmente diferenciamos el espacio como asociado dentro de una comunidad T, o a lo largo de una sección de la vía principal. Nuestro trabajo amplía la investigación relacionada con comunidades T al expandir su papel más allá de la preferencia residencial a la exploración de las redes de (des)conexión a través de las cuales se expresan las divisiones sociales por medio de prácticas de movilidad cotidiana. Concluimos que los residentes están significativamente menos inclinados a desplazarse dentro de áreas mezcladas o fuera del grupo, y que esto es especialmente el caso dentro de las comunidades T. Es también evidente que los residentes están más propensos a viajar a lo largo de las secciones fuera del grupo de una vía principal si lo hacen en un vehículo y que las mujeres mostraron una probabilidad no mayor que la de los hombres a desplazarse dentro de espacios catalogados como fuera del grupo. La evidencia de los rastros GPS da también mejores perspectivas dentro de algunas áreas donde parece ocurrir mezcla de comunidades.
Palabras clave: comunidades T, Irlanda del Norte, posconflicto, segregación, SIG.

There have been long-standing tensions between Protestant and Catholic communities in Northern Ireland over whether the region should remain part of the United Kingdom or become part of a united Republic of Ireland (Hughes et al. 2007; Brand 2009). These tensions have frequently erupted into violence, including the three decades between 1969 and 1998, known as "the troubles," which both reinforced and extended patterns of residential, political, and social segregation across the region. Although the Good Friday peace agreement, in place since 1998, has helped bring a degree of peace to Northern Ireland, deep-seated notions of Britishness or Irishness are still strongly evident. Harassment, intimidation, and occasional violence continue in cities such as Belfast, further fueling mistrust between communities (Brand 2009). Decades of violence restrict the mobility of those living in highly segregated neighborhoods, with residents rarely crossing sectarian boundaries, instead adjusting their movements and use of services in response to fear (Lysaght and Basten 2003; Shirlow and Murtagh 2006). Through the course of this article, we explore the extent to which evidence of this restricted mobility plays out in terms of movement through different types of group space in north Belfast.

Sociospatial Segregation in Belfast

Boal (1969) examined both residential and activity space segregation in the Shankhill and Falls communities (working-class areas of Belfast). In these areas, Protestants and Catholics are highly segregated yet live in close proximity to one another. Boal found a strong correlation between residential and activity space segregation, helping to explain ethno-sectarian immobility resulting from the presence of distinct territories. The layout of residential space through much of Belfast includes many cul-de-sacs and dead ends, which were intentionally used to segregate the two communities during the height of the region's conflict and continue to create segregation leading to territorial concentration, preserving community identity and a strong sense of "other" in relation to those beyond their community (Boal 1996). This attitude toward the other community was also observed by Shirlow and McGovern (1998), working in the Ardoyne area of Belfast. They reiterated the understanding that residential segregation both expresses and regulates ethno-sectarian animosity. In further work in the Ardoyne, fear of the other community was found to restrict mobility, affecting job-seeking, leisure, and consumption behavior (Shirlow 2000). Shirlow (2003) found that people living in deeply segregated areas developed an instinctive awareness of "safe" and "unsafe" places.

Peace walls also remain a significant territorial feature in Belfast today. Initially constructed by the British Army in response to sectarian violence (Byrne, Heenan, and Robinson 2012), these walls are material structures designed to reduce opportunities for conflict between opposing communities, providing some safety and security but also reinforcing sectarian segregation (Byrne et al. 2012; Donnan and Jarman 2016). Beyond physical barriers, varying forms of territorial marking both reinforce a sense of community identity within Belfast's neighborhoods and act as boundary markers between communities (Shirlow 2006). These include tangible symbols such as wall murals, flags (Jarman 2007), and painted curbs, as well as shared perceptions about who belongs where (Hughes et al. 2007; Brand 2009). The cumulative effect of these varying forms of sociospatial division is that in many cases basic services such as schools, playgrounds, libraries, leisure centers, and health services are used only by members of one community (Brand 2009), and residents have limited opportunity to interact across community divisions. Moreover, residents' free movement through the city's streets and the routes and pathways they select or avoid are powerfully shaped by their understandings of the local sectarian geography (Lysaght and Basten 2003; Huck et al. 2019). In this research, using a novel combination of Global Positioning System (GPS) tracking and geographic information system (GIS) data capture, we explore how Belfast residents' everyday movements are shaped by such understandings. As elaborated later, we focus particularly on the role of tertiary street networks or T-communities (Grannis 1998) in the reproduction of segregated mobility practices over time. Indeed, we argue that such networks could represent a fundamental building block of the sectarian patterning of activity space use in cities such as Belfast.

There is limited literature that explores gender differences in mobility resulting from the segregation of urban street networks in Belfast, and this represents a second focus of this research. Available evidence suggests, at least anecdotally, that women might feel more confident entering neighborhoods of the opposing community (Lysaght and Basten 2003). A study into mobility and access to leisure facilities suggests, for example, that 62 percent of nonpensioners crossing the community divide for leisure purposes were women (Bairner and Shirlow 2003). Research from interviews conducted during the troubles also implies that, due to assumed political innocence and a mutual agreement that women and children were not legitimate targets, some women felt a greater confidence crossing the peace line in West Belfast (Dowler 2001). Although there is some evidence here to suggest that women are potentially more willing to enter out-group areas, this evidence has not explored concrete patterns of movement in and through everyday spaces. We therefore explore this idea further to see whether our evidence supports the idea that women move more freely than men within out-group spaces.

Lysaght and Basten (2003) suggested that for those with access to a car it might be possible to overcome some of the spatial divisions that exist within a segregated city. The greater sense of safety and reduced opportunity for interaction derived when traveling in a vehicle suggest a greater likelihood that people will enter out-group or mixed spaces when traveling in a vehicle than when traveling on foot. In other words, a vehicle could act as a kind of spatial "bubble" that potentially insulates residents from forms of threat that are experienced more acutely when they travel as pedestrians, thus allowing them to cross sectarian boundaries. We explore this hypothesis further during our analysis.

Segregation, T-Communities, and Everyday Mobility Practices: From Predefined Areal Units to Tertiary Street Networks

This research aims to extend existing research on sectarian divisions in Belfast in two main ways. We extend Grannis's (1998, 2005) work on the role of so-called T-communities in maintaining racial segregation in large U.S. cities to the context of sectarian segregation in Belfast, Northern Ireland's capital city. As a novel contribution to the field, we show how such T-communities are central in shaping the everyday mobility practices of local Catholic and Protestant residents. In effect, they are central to maintaining networks of disconnection in this historically divided city.

Many segregation studies use predefined areas such as census boundaries to define neighborhoods and measure the nature and extent of urban segregation (Omer and Benenson 2002; Noonan 2005; Lloyd 2010; Wong and Shaw 2011; Weaver 2015; Li and Wang 2017; Merrilees et al. 2017). Grannis (2009) stressed that although boundaries defined by census or other administrative agencies generate statistical units that are useful for summarizing data, they do not delineate neighborhoods in a socially meaningful way or account for the potential for residents to interact. Census boundaries seldom map onto residents' own perceptions or behaviors, which are important if the causes and consequences of segregation are to be determined (Deng 2016). For example, physical barriers such as open spaces, railways, or major roads have been found to affect segregation (Noonan 2005); yet such barriers are often disregarded in the largely administrative definition of census boundaries. The geographic context relevant to individuals themselves might thus not necessarily relate to officially delineated geographic units (e.g., wards, districts, or other census units; Kwan 2012). In the context of this study, the actual and perceived potential for interaction with specific group members is important for understanding both the nature of segregation and its consequences for the everyday mobility practices of individuals.

The challenges relating to use of census boundaries for neighborhood delineation are evident in north Belfast. Here some census small areas (the smallest reporting unit for the Northern Ireland census) appear to be highly mixed, yet as the example in Figure 1 shows, the area is, in fact, highly divided. On closer inspection of the small area shown as mixed in Figure 1A, it can be seen that there is no route, pedestrian or otherwise, between one side of the census small area and the other without crossing the boundary of the census small area. In fact, divided by a peace wall, this small area straddles an interface between highly segregated neighborhoods. This suggests not only that community affiliation is poorly defined but also that the census boundaries do not form part of a cohesive neighborhood definition.

The concept of T-communities was introduced by Grannis (1998), whose hypothesis was that relational connections via tertiary streets were a better predictor of the racial composition of neighborhoods than either simple proximity or distribution across census units. By studying two cities with very different social and geographic backgrounds, Los Angeles and San Francisco, Grannis (1998) tested this hypothesis, finding that those residents connected via tertiary streets were much more similar than those not connected through a tertiary street network. He concluded that those "down the street"—regardless of distance—are more similar to each other than those who might be closer by straight-line distance but less connected. Grannis (1998) also highlighted that residents living within the same census area do not have the same opportunities for contact as those living within the same T-communities. This concurs with our own observations as demonstrated earlier in Figure 1, which indicates how interaction between residents who share a census tract might nonetheless be limited by territorial boundaries and the (dis)connection of existing street networks.

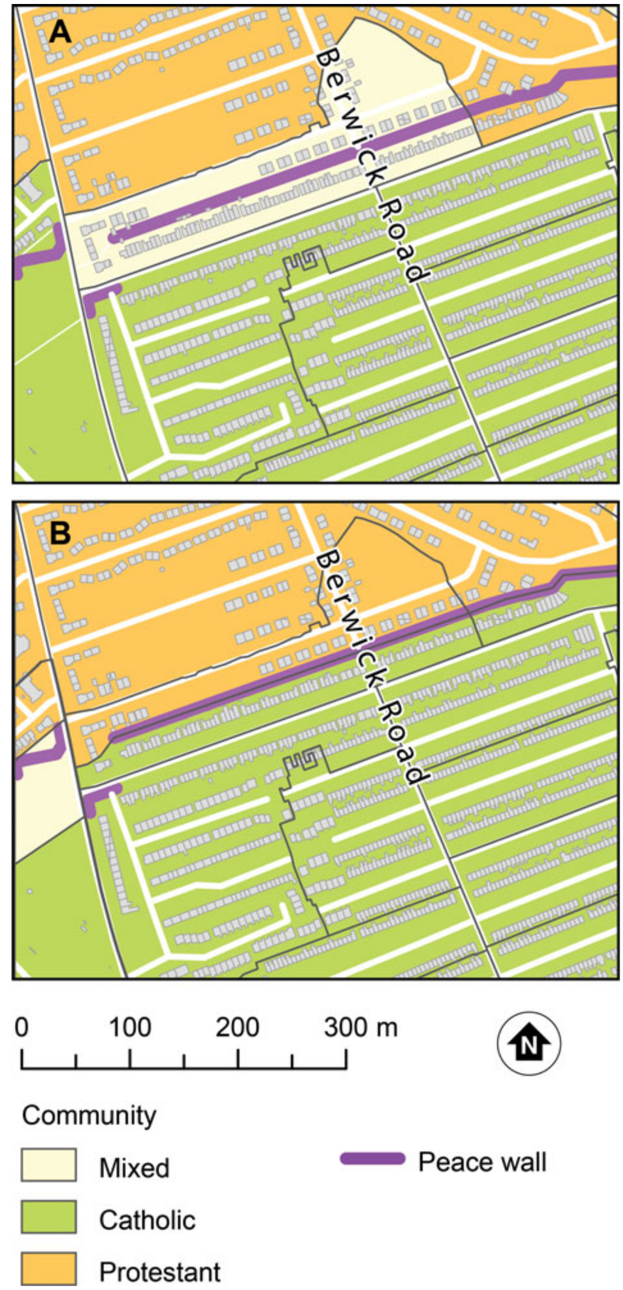

Figure 1. (A) Community definitions based on UK population census small area statistics for 2011. Areas defined based on greater than 65 percent Catholic or Protestant. (B) Adjusted community definition accounting for street layout, presence of peace walls, and known community boundaries. (Color figure available online.)

Grannis (2005) later went on to study variations within T-communities, this time studying the cities of Los Angeles, New York, and Chicago. There he concluded that T-communities and their role in social connectivity between residents who view themselves as similar were a major factor in individuals' decisions regarding where they choose to live. The T-community concept suggests that the geographic opportunities for everyday "passive" contacts, which tertiary street networks facilitate, could lead to opportunities for active contact between residents and the building of a sense of community (Weaver 2015). For these reasons, individuals' residential preferences reflect not only simple relations of physical proximity but also relations of real and imagined connection, a sense of who lives down the street and who is likely to be encountered in everyday life while engaging in mundane activities such as going to the shops, visiting a friend, walking the dog, or simply taking a stroll.

Grannis (1998) defined tertiary streets as pedestrian-oriented streets that are not used as throughways but are designed to connect local residents with a sociospatial network of seemingly "trivial" streets. Where two or more tertiary streets interconnect, they are considered part of the same T-community, but once a tertiary street interconnects with a main road or other barrier, the outer limit of the T-community is defined (Figure 2). T-communities also account for other boundaries that might separate neighborhoods, including parks, shopping malls, or physical barriers such as walls (Grannis 1998). Although there might always remain some uncertainty about the true geographic context affecting individuals (Kwan 2012), T-communities help to focus defined neighborhoods around opportunities for interaction, which is particularly important when considering segregation and mobility. The interconnections and opportunities for interaction facilitated by T-communities, we would argue, thus provide a more meaningful definition of spatial units for segregation studies than more commonly applied census boundaries.

If, as Grannis (1998) suggested, T-communities influence opportunities for interaction, then we might predict higher levels of activity space segregation (and lower levels of mixing) within them than within nontertiary streets. As discussed later, this research thus aimed to explore the extent to which sectarian segregation of mobility practices varies between tertiary and nontertiary streets, focusing on relations in the northern area of the historically divided city of Belfast. Our main objective here was not to directly compare the analytic utility of standard

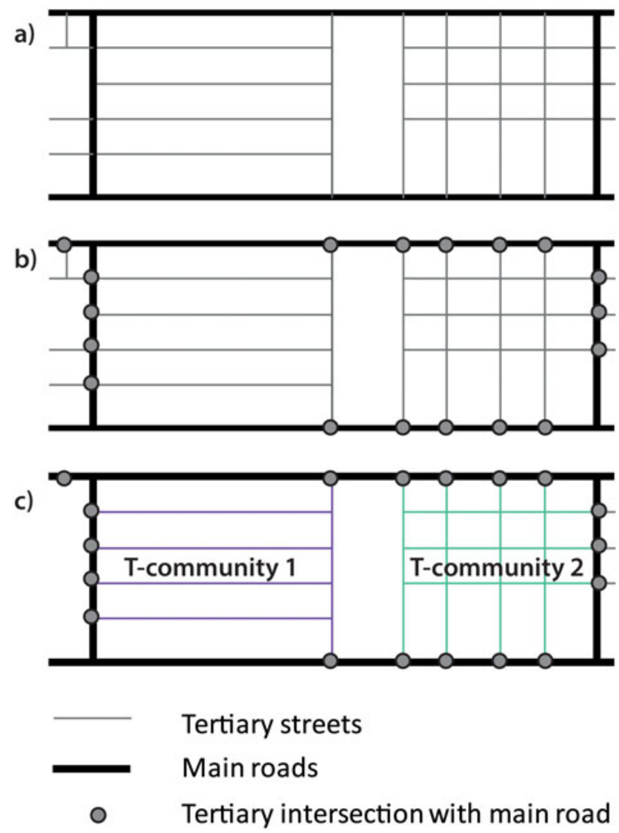

Figure 2. The T-community concept: (A) distinguish main roads from tertiary streets, (B) identify intersections between tertiary streets and main roads (or other barriers), (C) group tertiary streets into T-communities, terminating the T-community when it reaches an intersection with a main road. (Color figure available online.)

census units with T-communities as a foundational unit of analysis in residential segregation research, a comparison that Grannis has already developed (e.g., Grannis 1998). Rather, our objective was more novel, namely, to explore the potential role of T-communities in shaping how residents use everyday pathways and activity space beyond their homes.

Research Focus and Questions

Regardless of how neighborhoods are defined, many segregation studies focus exclusively on residential segregation, often using census data to define the ethnic mix of the residential population (Grannis 1998; Hughes et al. 2007; Lloyd and Shuttleworth 2012; Bruch 2014). Although some studies have measured use of space through activity diaries (Wong and Shaw 2011; Farber et al. 2013; Li and Wang 2017) or from mobile phone usage (Silm and Ahas 2014; Järv et al. 2015), few studies have used GPS tracking for understanding the impact of segregation on mobility (Palmer et al. 2013; Roulston et al. 2017). GPS tracks potentially identify locations that people visit when not at home, as well as the routes people take to reach these locations. To date the T-community concept has only been used for studies of residential segregation in large grid plan cities (Grannis 1998, 2005). Meanwhile work using GPS tracks to measure time in neighborhoods of differing characteristics has relied on census units to define neighborhood boundaries (Palmer et al. 2013). By combining T-community neighborhood definitions with GPS tracks collected by residents, we gain new insights into the way in which people use different types of group space (in-group, mixed, and out-group) and different neighborhood types (T-communities, main roads). To explore the impact of segregation on residents' everyday movements, the study focuses entirely on time spent in transit, moving through open space, and excludes time spent at destinations.

Fear of the opposing community, either real or perceived, leads to negative emotional responses toward out-group areas (Shirlow 2003; Roulston et al. 2017), suggesting therefore that residents would be less likely to spend time moving within out-group areas. This is the first assumption that we seek to test. We then explore a second assumption that time spent in out-group space is less likely to be within T-communities and more likely to be along sections of main road that are used as through routes or for access to services, including access to supermarkets and retail parks. Based on the suggestion that fear is reduced when traveling in a vehicle (Lysaght and Basten 2003), we will test whether mode of transport affects the likelihood of entering out-group or mixed spaces. Finally, based on suggestions in the literature that women might be more willing to enter out-group space, we explore this idea further using data from a sample of local residents to determine whether there is any greater likelihood that women will enter out-group spaces than men.

Combining GPS tracking and T-community definitions, we address the following research questions:

1. Do residents of north Belfast spend significantly more time moving within areas of their own community affiliation (in-group areas) than within out-group or mixed spaces?
2. Of time spent within out-group space, is this more likely to be along sections of main road than within out-group T-communities?
3. Does mode of transport affect mobility, with people traveling in vehicles more likely to enter mixed or out-group space?
4. Do women spend more time within out-group areas than men?

Methods

In this section, we outline the data inputs used and analysis undertaken, focusing on the challenge of studying how T-communities might shape everyday mobility practices in north Belfast, and how this could be affected by factors such as mode of transport and gender. The key steps are summarized in the flow diagram in Figure 3.

Study Area

This study focuses on the area of north Belfast. Whereas east Belfast is predominantly Protestant and west Belfast is predominantly Catholic, north Belfast has approximately even numbers of Catholics and Protestants living side by side in highly segregated communities, as illustrated in Figure 4. It is also within this part of the city that physical barriers to movement, in the form of peace walls, are most prevalent (Figure 4). Both the close proximity of opposing communities and the presence of peace walls in north Belfast potentially affect people's everyday mobility patterns, therefore making it an interesting focus for this study. Figure 5 illustrates the way in which peace walls divide tertiary streets that would once have connected communities. The example shown in Figure 5 is a section of a 650-m-long fence, which now divides a once-joined T-community into two disconnected communities. Here it evident that the tertiary street, Berwick Road, once connecting the two communities has been truncated. Regardless of any preference for avoiding out-group communities, it is obvious that the presence of peace walls themselves has affected everyday mobility in Belfast.

North Belfast experiences high levels of deprivation, with half of the residents living in the top 20 percent of most deprived wards in Northern Ireland. Deprivation levels are very similar for both the Protestant and Catholic communities in this study. The research here is part of a wider study exploring

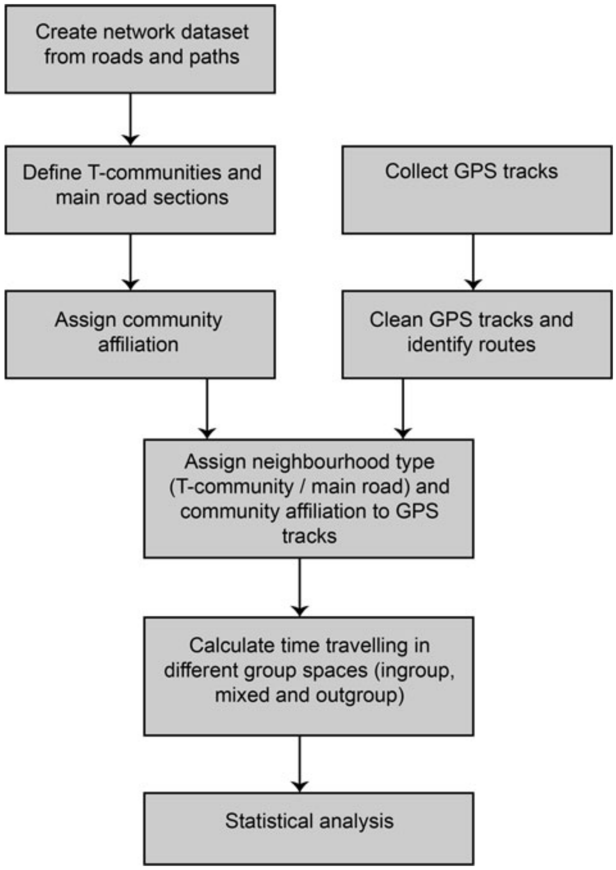

Figure 3. Summary of steps in the methodology.

mobility and segregation in north Belfast (Hocking et al. 2019; Huck et al. 2019). Of all participants taking part in the study, 73 percent had a household income of less than £20,000 per year, with very little variation between community groups. Variation in economic status or deprivation is therefore excluded from subsequent analysis.

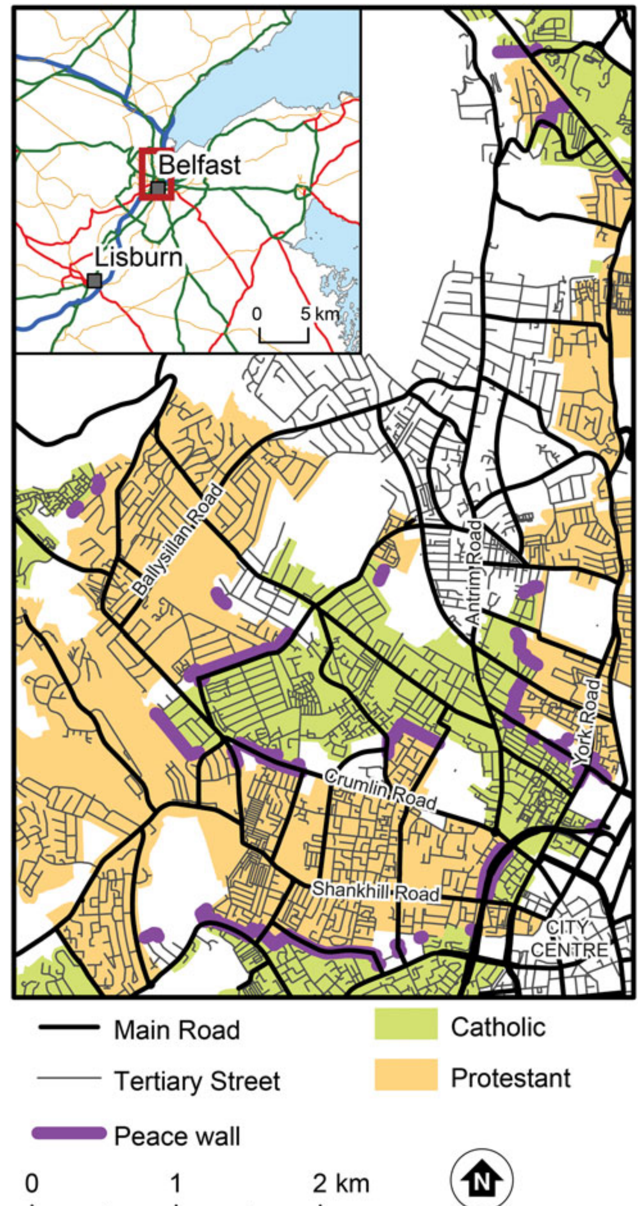

Figure 4. Study area: Catholic and Protestant communities within the study area of north Belfast, defined as census small areas with greater than 65 percent of residents identifying with this community during the 2011 Census of Population and where strong community identity is known to exist. Large nonresidential spaces and mixed neighborhoods are shown in white. (Color figure available online.)

Defining T-Communities

We began by creating a network data set representing all roads and paths within north Belfast. This was derived from a road data set supplied by the Ordnance Survey Northern Ireland (OSNI) from which we captured additional residential footpaths visible on either Google Maps or the OSNI 1:10,000 background maps. Tertiary streets and footpaths within residential areas were defined as traversable. Features such as main roads, peace walls, industrial areas, retail complexes, and parks were defined as non-traversable and used as barriers within the network, thus defining boundaries for the T-communities. The T-communities were computed using ArcGIS Desktop 10.4 (ESRI 2015) network analysis tools to generate service areas representing all sets of connected streets before a barrier is reached (see Figure 6A for examples of defined T-communities). A fuller description of the method for creating T-communities can be found in the Supplemental Material.

One of the key distinctions between Grannis's (1998) original definition and our implementation of

Figure 5. (A) Aerial image showing the division of the tertiary street, Berwick Road, by a peace wall. (B) Photo highlighting the impact of the barrier, on the Catholic side of the peace wall with evidence of painted murals. (C) Photo highlighting the impact of the barrier, on the Protestant side of the peace wall. (Color figure available online.)

T-communities is the treatment of main roads. Using Grannis's definition, only roads not suitable for pedestrians are defined as main roads (Grannis 2005). By this definition, however, north Belfast would only form one T-community. Using our refined definition of main roads as those wide enough for two cars to pass and known as through routes, a more meaningful set of T-communities was created for studying segregation at a finer scale and in a context with a very different road structure. In Grannis's (1998) work, the main roads are then of little interest to further analysis of segregation. In the context of north Belfast, however, the main roads used to delineate boundaries to T-communities are of interest themselves. These main roads are well used as pedestrian routes and are often lined with residential properties. They accordingly convey sectarian territorial meanings. In addition to defining distinct T-communities, main roads were broken into sections at key junctions or known community divides (Figure 6B; see Supplemental Material for more information). In total, there are 391 T-communities and 212 main road sections within the study area, compared to 411 census small areas.

Assigning Community Affiliation

Although it is common to define the community affiliation of a neighborhood using census data, this can in some instances be misleading. For example, in north Belfast some census zones (census small areas) that appear mixed based on even numbers of Catholics and Protestants can be some of the most divided, such as the established Protestant community

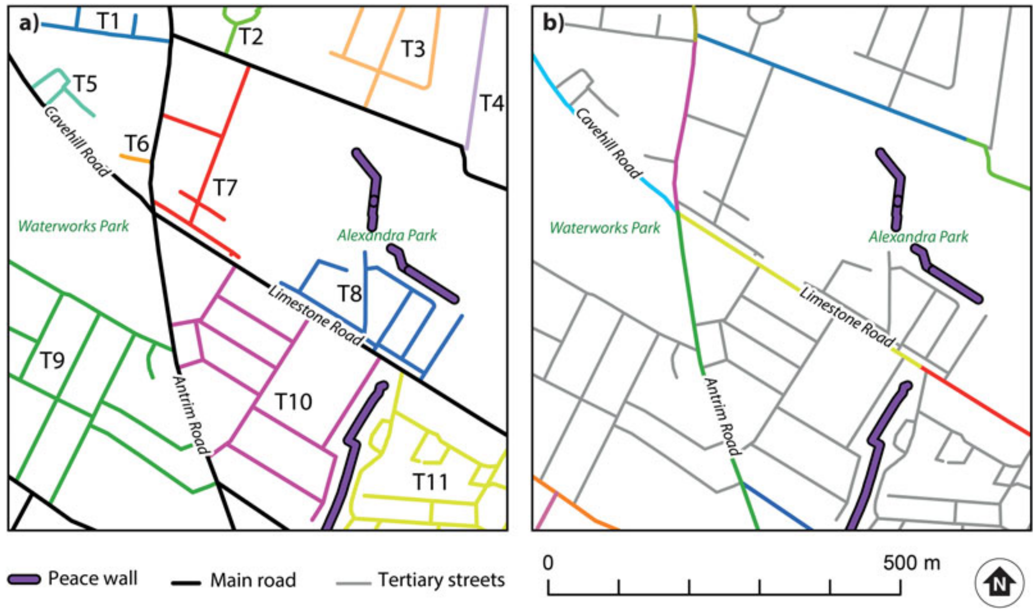

Figure 6. An illustrative section of north Belfast showing (A) defined T-communities (labeled T1–T11) and (B) sections of main roads. (Color figure available online.)

of Greencastle (Huck et al. 2019). Although census zones follow street patterns to some extent, they are often optimized to account for the number of households that they contain rather than aligned to community or neighborhood divides. It is therefore possible for census zones to be constructed across a clear community divide. In some instances, the divide is not only a perceived one but is also a physical barrier, with peace walls dividing census zones (as demonstrated in Figure 1). Using extensive local knowledge of the research team, the location of barriers (Belfast Interface Project 2017), and existing census data, census zones straddling a community divide were split and community affiliation was redefined accordingly. Areas were defined as either Catholic, Protestant, or mixed where it was known that a clear sense of community identity existed or mixing occurs, and was supported by census statistics. This definition was used to assign community affiliation to the T-communities. Unlike the census small area boundaries, no T-communities were found to straddle a known community divide. Community affiliation of sections of main road were defined, using the same community definition and with further refinement and advice from the Institute of Conflict Research, a nongovernmental organization located on a sectarian interface in north Belfast that has conducted research on segregation for more than twenty years.

GPS Tracking

Participants for GPS tracking were recruited to the project during a one-year field campaign, in which two project researchers went door to door throughout north Belfast asking all householders who answered the door to participate by installing a custom application on a GPS-enabled Android smartphone and collecting data for a period of up to fourteen days (see Hocking et al. [2018], for more details of the process of recruiting particpants). From this field campaign, 233 recruits agreed to install the tracking application and registered some data. The application automatically captured points every four seconds and uploaded the data to a remote server once connected to Wi-Fi (Whyatt et al. 2016). Locational accuracy of GPS track points varies depending on a number of factors, including alignment of satellites, the quality of the receiver, and the presence of blocking features such as buildings and trees. Signal indoors is usually poor. The GPS data were cleaned to remove points with poor positional accuracy. The continuous sequence of points for each participant was also divided into separate tracks and stop locations. Details of the data cleaning process and the method used to separate tracks can be found in Davies et al. (2017). A total of 184 (86 Catholic, 87 Protestant, and 11 other) users recorded at least one valid track, where a route between two locations could be distinguished. These were used in the subsequent analysis. The number of tracks varied from one to 200 per participant, with a mean of thirty-three per participant. A total of 6,158 separate tracks and stops were defined. The average age of participants was thirty-nine (this was the same for both Catholic and Protestant participant groups). Of the participants whose data were used for this study, 62 percent were female and 38 percent were male. There was a slight variation in gender split between community groups, with 57 percent female in the Catholic group and 70 percent female in the Protestant group.

Travel mode has a potentially significant influence on an individual's willingness to move within out-group areas (Lysaght and Basten 2003). Because the mobile app did not capture travel mode, mode was inferred based on the work of Bohte and Maat (2009). Participants were assumed to be on foot if the average track speed was less than 10 km/hr and the maximum track speed was less than 14 km/hr, in a vehicle if the average track speed was greater than 25 km/hr or maximum track speed was greater than 45 km/hr, and indeterminate for all other speeds, which could represent bicycling, slow-moving traffic, or a mixed-mode journey.

GPS track points were assigned T-communities or main road sections by first snapping all points within 20 m of a main road to those roads. This ensured that track points near junctions with tertiary streets remained associated with main roads. All remaining points within 40 m of a road were snapped to the nearest road section, assuming that all points further than 40 m from a road were associated with movement through open spaces such as parks. At this stage attributes from the assigned T-community or main road were joined to the GPS track points, including the community affiliation of the T-community. From this it was possible to ascertain whether the track points were in-group (same community affiliation as the participant), mixed (either participant affiliation was other or neighborhood was mixed), or out-group (community affiliation was opposite to the participant). User ID, track ID, time, travel mode, participant's community affiliation and gender, and type of group space (in-group, mixed, out-group) were associated with each track point prior to the statistical analysis.

Statistical Approach

To address the research questions specified earlier, taking into account the structure of our data, which involved repeated measurement of participants from different groups, genders, and T-communities, we used mixed linear modeling with random intercepts for participants, implemented in the statistical programming language R (R Core Team 2018) and the package NLME (Pinheiro et al. 2018). Modeling our data with mixed linear methods allowed us to test the hypothesis that residents would spend more time moving within in-group areas (a main effect) and that when moving through out-group or mixed areas they would be more likely to do so along main roads (an interaction of type of group space and type of road). It also allowed us to test the hypothesis that residents would be more likely to move through mixed or out-group spaces in a vehicle rather than on foot (an interaction of mode of transport and type of group space), as well as the hypothesis that women would spend more time within non-in-group areas than men. To control for variable amounts of GPS tracking data captured from participants, which resulted in positively skewed distributions, time estimates were first aggregated per person and then log-transformed.

Factors for analysis included type of group space (in-group, mixed, out-group), community membership (Catholic/Protestant), travel mode (by vehicle or on foot), and neighborhood type (main road vs. T-community). A further covariate was added into the analysis to control for opportunity for road usage across group space and neighborhood type. This covariate represented the proportion of main roads and tertiary streets within 1 km of a participant's home that was within in-group, mixed, or out-group space. The dependent variable was the log-transformed, summed amount of time in minutes that each individual spent in different types of spaces using different modes of travel. This measure was used to generate, among other things, aggregate scores of the time spent by different community groups across different spaces. The mixed linear model fitted to the data had fixed effects for group space, community membership (Catholic/Protestant), travel mode, neighborhood type, and the road usage covariate, as well as a random intercept effect for participants. Modeling was carried out in a top-down fashion, as recommended by Zuur et al. (2009); that is, nonsignificant higher order model classes were removed iteratively and nonsignificant individual terms were removed from the highest remaining order of model class.

Results

We present results for each of the research questions in the order specified earlier and repeat the research questions for sake of clarity of presentation.

1. Do residents of north Belfast spend significantly more time moving within areas of their own community affiliation (in-group areas) than within out-group or mixed spaces?
2. Of time spent within out-group space is this more likely to be along sections of main road than within out-group T-communities?

Overall, participants spent considerably more time moving within in-group areas than within mixed or out-group areas. Figure 7 suggests that for sections of main road there is an ordinal pattern for time spent in types of group space (in-group > mixed > out-group). Whereas the pattern of preference for in-group space holds for both main roads and T-communities, the pattern is much more striking for time spent within T-communities, where very little time is spent within mixed or out-group areas. This is borne out by the significant interaction for group space and neighborhood type in the mixed linear model, as shown in Table 1. Our results therefore not only confirm the preference for moving within in-group space but also clearly demonstrate that time spent within out-group space is more likely to be along sections of main road.

Figure 8 further illustrates the finding that participants were significantly less likely to move within out-group T-community space. This shows that along main roads there is movement within in-group, mixed, and out-group spaces, with a slight preference toward movement within in-group spaces. For the majority of T-communities, however, it is evident that most movement occurs within in-group space. Although the majority of mixing between in-group and out-group usage occurs along main roads, pockets of out-group movements within tertiary streets occur across the map, usually relating to a single trip by one participant (e.g., Location C in Figure 8). In some areas where a greater amount of mixing appears present within tertiary streets, there are possible explanatory factors. For example, Location A on the map shows the location of Holy Cross Girls Primary School. This is a Catholic primary school situated within a Protestant neighborhood. Tracks within this area, recorded as movement within out-group space, are all timed at the start or end of the school day,

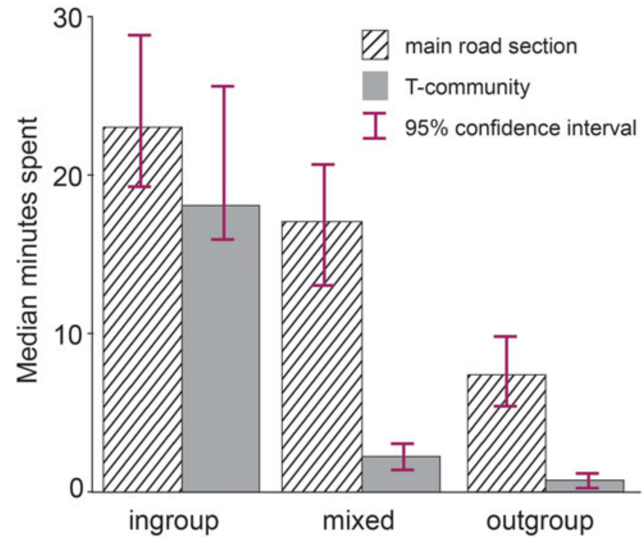

Figure 7. Median minutes spent along main roads or within T-communities, across types of group space. *Note:* The confidence intervals were estimated by bootstrap (1,000 replications). (Color figure available online.)

suggesting that taking children to or from the Holy Cross School offers a clear explanation of the use of this out-group space. There is also strong evidence of movement within out-group space around Location B. This is a predominantly Catholic area, which includes the location of the Belfast Royal Academy (a mixed grammar school). The timing of out-group movement in this area is more varied, typically at the start and end of the working day and at lunchtime.

Although the nonoverlapping confidence intervals in Figure 7 suggest clear differences in the patterns of time spent within sections of main road or T-communities across different group spaces (in-group, mixed, out-group), this could be an artifact of participants' home locations rather than preference for in-group space. We therefore introduced a covariate into the analysis to control for the opportunity of road usage across group space and neighborhood type (main road section, T-community). Having carried out a secondary analysis to account for the types of roads and group spaces within close proximity of a participant's home location, results showed that although the control for home location was significant in explaining use of group space, preference for in-group space remained significant. Table 1 shows the modified analysis of variance table, which confirms that even controlling for home location, people were significantly less likely to spend time within out-group space. Table 1 shows that home location

Table 1. Analysis of variance table for mixed linear model containing two-way interaction of group space and neighborhood type, controlling for home location

	SS	MS	df_1	df_2	F	$p <$
Group space	292.55	146.28	2	1,580.8	77.742	0.001
Neighborhood type	382.67	382.67	1	1,545.4	203.379	0.001
Control for home location	33.61	33.61	1	1,641.6	17.862	0.001
Group space × Neighborhood type	115.08	57.54	2	1,507.5	30.582	0.001

Notes: SS = sum of squares; MS = mean square; *df* = degrees of freedom; *F* = value of *F* distribution statistic; *p* = probability.

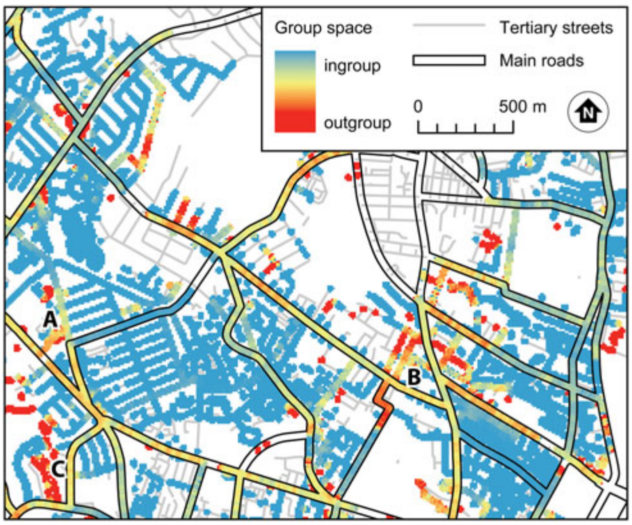

Figure 8. Movements captured from participants' Global Positioning System tracks within north Belfast. Shading ranges from blue (track points show participants moving within in-group areas) to red (track points show participant movement within out-group spaces). Blended colors show mixed patterns of movement within in-group and out-group areas. (Color figure available online.)

had a significant overall effect on time spent across different kinds of spaces, $F(1, 1641.6) = 17.86$, $p < 0.001$; however, above and beyond this effect, type of group space, neighborhood type, and, crucially, the group space by neighborhood type interaction all remained statistically significant. Examination of the residuals from the model suggested possible heteroskedasticity (an important assumption underlying the calculation of probability values), and we therefore computed bootstrap 95 percent confidence intervals (1,000 replications) for model parameter estimates as an alternative, distribution-independent check on model effects. All effects reported as significant in Table 1 also had confidence intervals that were either entirely positive or entirely negative, supporting the findings in Table 1. Model parameters, with confidence intervals, are shown in Table 2.

For the statistical analysis, all zero values were removed, meaning that only participants who spent at least sometime within an out-group area were included in the analysis. This removed from the analysis 21 percent of participants, who never recorded any movement within out-group space. In light of this, the clear preference found for use of in-group rather than out-group space is a conservative estimate of the impact of segregation on movement. The overall use of out-group T-communities is particularly low, constituting less than 2 percent of the overall movements captured within the GPS tracks.

In summary, our results show that residents of north Belfast spend significantly more time moving within areas of their own community affiliation (in-group areas) and that time spent within out-group space is more likely to be along sections of main road than within T-communities. The overall implication is that segregation is widespread within north Belfast and that it is expressed most starkly via everyday patterns of movement within networks of tertiary streets (T-communities).

3. Does mode of transport affect mobility, with people traveling in vehicles more likely to enter mixed or out-group space?

Initial examination of the two-way interaction between group space and travel mode, shown as part of Table 3, suggested that there was no significant interaction between travel mode and group space ($p \leq 0.202$) in predicting time spent. Further exploration of the three-way interactions between group space, neighborhood type, and travel mode, shown in Figure 9, revealed that movement along out-group or mixed sections of main roads was significantly more likely to occur within a vehicle than on foot. In contrast, we found no significant differences for travel mode within mixed or out-group T-communities. Model parameters, with confidence intervals, are shown in Table 4.

We found that the combination of mode of transport and type of road had little influence on the use

Table 2. Model coefficients (fixed effects, with bootstrapped 95 percent confidence intervals, 1,000 repetitions)

	b	*SE*(*B*)	*B*	Lower CI	Upper CI
(Intercept)	2.14	0.10		1.94	2.33
Group space: out-group vs. in-group	−0.47	0.12	−0.12	−0.72	−0.24
Group space: shared vs. in-group	−0.29	0.11	−0.08	−0.51	−0.08
Neighborhood type: T-community vs. main road	−0.52	0.13	−0.15	−0.77	−0.29
Control for home location	0.01	0.00	0.12	0.01	0.02
Group space: out-group vs. in-group × Road type: T-community vs. main	−1.40	0.18	−0.26	−1.71	−1.02
Group space: shared vs. in-group × Neighborhood type: T-community vs. main road	−0.60	0.17	−0.12	−0.89	−0.25

Notes: b = unstandardized coefficient; *SE* = standard error; *B* = standardized coefficient; CI = confidence interval.

Table 3. Analysis of variance table for mixed linear modeling of time spent within in-group spaces by travel mode, community, and neighborhood type

	SS	MS	df_1	df_2	*F*	$p <$
Group space	174.99	87.49	2	899.96	63.64	0.001
Travel mode	18.73	18.73	1	953.82	13.63	0.001
Neighborhood type	140.27	140.27	1	886.45	102.04	0.001
Control for home location	7.03	7.03	1	906.94	5.12	0.024
Community	0.00	0.00	1	164.15	0.00	0.993
Group space × Travel mode	4.41	2.21	2	896.90	1.60	0.202
Group space × Neighborhood type	35.57	17.79	2	876.96	12.94	0.001
Neighborhood type × Travel mode	51.30	51.30	1	869.85	37.32	0.001
Group space × Travel mode × Neighborhood type	10.55	5.27	2	871.21	3.84	0.022

Notes: SS = sum of squares; MS = mean square; *df* = degrees of freedom; *F* = value of *F* distribution statistic; *p* = probability.

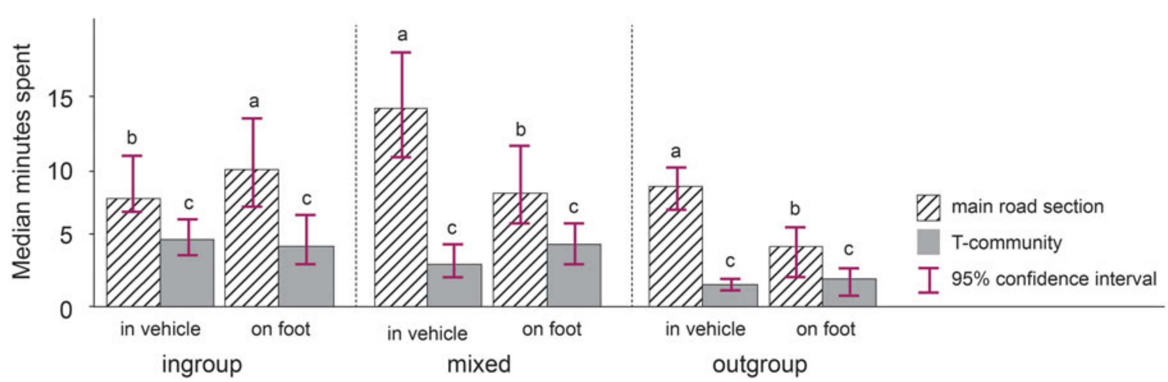

Figure 9. Median minutes spent in different group spaces by transport mode. Letters above bars indicate significantly different post hoc contrasts (Tukey). Different letters indicate a significant difference at $p < 0.05$. Thus, in the far right panel, a > b > c = c, indicating that participants spent significantly more time in out-group main road sections when in a vehicle than when walking in such sections or either walking or driving in T-communities. (Color figure available online.)

of in-group space. However, several effects emerged for mixed and out-group spaces when considering the same combination. Notably, along main roads, residents were more likely to move within mixed or out-group spaces when in a vehicle, rather than on foot. Mode of transport, however, had no effect on the time spent in mixed or out-group spaces when those spaces were part of the T-communities. Thus, traveling in a vehicle might enable residents to spend more time on main roads outside their own community spaces, but it has no effect on the use of mixed or out-group spaces that are within T-communities.

4. Do women spend more time within out-group areas than men?

Table 4. Model coefficients (fixed effects, with bootstrapped 95 percent confidence intervals, 1,000 repetitions)

	b	*SE*	*B*	Lower CI	Upper CI
(Intercept)	2.73	0.15		2.43	3.04
Group space: in-group vs. out-group (1)	−0.52	0.14	−0.14	−0.80	−0.24
Group space: in-group vs. shared (2)	−0.28	0.14	−0.07	−0.57	0.01
Travel mode	−0.68	0.16	−0.19	−0.98	−0.39
Neighborhood type	−0.76	0.17	−0.23	−1.11	−0.42
Control for home location	0.01	0.00	0.08	0.00	0.01
Community	0.00	0.17	0.00	−0.34	0.33
Group space: (1) × Travel mode	−0.50	0.31	−0.07	−1.08	0.03
Group space: (2) × Travel mode	−0.14	0.26	−0.02	−0.67	0.41
Group space: (1) × Neighborhood type	−1.52	0.22	−0.29	−1.98	−1.12
Group space: (2) × Neighborhood type	−1.07	0.23	−0.20	−1.54	−0.64
Travel mode × Neighborhood type	0.48	0.22	0.11	0.03	0.90
Group space: (1) × Travel mode × Neighborhood type	0.89	0.43	0.08	0.07	1.74
Group space: (2) × Travel mode × Neighborhood type	0.90	0.38	0.10	0.10	1.66

Notes: *b* = unstandardized coefficient; *SE* = standard error; *B* = standardized coefficient; CI = confidence interval.

Table 5. Analysis of variance table for mixed linear modeling of time spent in in-group spaces by gender, neighborhood type, and group space

	SS	MS	df_1	df_2	*F*	*p*
Group space	241.70	241.70	1	944.10	136.38	<0.001
Gender	2.74	2.74	1	168.50	1.55	0.215
Neighborhood type	144.53	144.53	1	971.28	81.55	<0.001
Control	8.84	8.84	1	1,034.35	4.99	0.026
Group space × Gender	0.19	0.19	1	954.74	0.11	0.745
Group space × Neighborhood type	98.69	98.69	1	921.49	55.68	<0.001
Gender × Neighborhood type	1.06	1.06	1	908.16	0.60	0.441
Group space × Gender × Neighborhood type	0.37	0.37	1	909.63	0.21	0.649

Notes: SS = sum of squares; MS = mean square; *df* = degrees of freedom; *F* = value of *F* distribution statistic; *p* = probability.

We tested whether men and women spent different amounts of time in different group spaces, but we did not find a significant effect. The only notable effect we found for gender in all of our analyses was a marginally significant interaction between gender and mode of transport in a four-way mixed linear model (extending the three-way model reported in Table 5 by adding mode of transport). This showed that there was a significant likelihood that men would travel within a vehicle and that women would walk. In general, though, our results do not support the hypothesis that women would spend more time in mixed or out-group spaces, whether located along main roads or within T-communities.

Discussion

In reflecting on the methodology applied and results obtained, we first examine the findings in relation to the hypothesis set, which explores the impact of segregation on people's mobility, particularly in the context of movement within defined T-community spaces. We then discuss challenges of adapting the T-community concept to a very different setting than its original implementation, examining the extent to which this is useful for further segregation studies.

Perhaps unsurprising, given the history of conflict within north Belfast and the continued presence of sectarian markers in the landscape, including physical barriers such as peace walls, our results show that residents of north Belfast spend significantly more time moving within in-group spaces than within either mixed or out-group areas. What is more interesting is that this pattern is significantly stronger within T-communities than along main roads, suggesting that it is within networks of tertiary streets (T-communities) that segregation remains at its strongest. Given Grannis's (1998) premise that opportunities for interaction between residents create identity within T-communities, and thereby shape residents' choices about where and with whom they want live (Grannis 1998), it is perhaps unsurprising that no T-communities straddle a community divide and that very little movement occurs within out-group T-community space. Where use is made of out-group T-community space this is often for specific reasons, such as access to Holy Cross Primary School, a Catholic school situated within a predominantly Protestant T-community (Figure 8, Location A). At the same time, past tensions around areas such as Holy Cross serve to highlight tensions and fear related to entering out-group neighborhoods (Gilligan 2009; Young 2017).

Along main roads there is still a preference for use of in-group space, but this effect is less pronounced than within T-communities. One explanation for this is that journeys along main roads beyond in-group space are necessary to access other parts of the city, as well as key services and facilities within north Belfast that might be located along main roads in or beyond out-group spaces. Travel along main roads, typically in vehicles between an individual's home T-community and a neutral nonplace such as a supermarket, limits interactions with people or symbols of sectarianism such as flags or graffiti (Huck et al. 2019). Although there is significantly more use of out-group sections of main roads compared to T-communities, evidence from walking interviews (see Hocking et al. [2019] for details) conducted as part of the wider project, of which this study is one part, suggests that there remains a clear sense of defined community territories along main roads. In some cases, community members know which side of the road they need to walk on to feel safe. During his walking interview, one participant (a male Protestant) had a clear notion of where he did and did not feel safe and the best route through an opposing out-group area. Reference here to "the Shankhill" relates to an area of shops along Shankhill Road. Both Shankhill Road and Crumlin Road are main roads that lead into the city center.

> I know that's Catholic, so therefore that would stop me from going in that direction. If I could avoid going in the direction of a Catholic area, hence, this is why I would go this way because I would feel very vulnerable going down through Alliance Avenue. Be very vulnerable down Ardoyne Road. But on this road, it runs straight down, straight down to Twaddell Avenue, Woodvale, Crumlin Road. And if I was going to the Shankill for instance to go to a shop, I'd walk on that side of the road [right hand if headed in the direction of town], and right down to that corner.

In exploring the impact of mode of transport on mobility, it is clear that participants are more likely to travel along out-group sections of main roads if they are in a vehicle. This is interesting because it qualifies the supposed "bubble" effects of being enclosed within a motor vehicle. Being within a vehicle might cause residents to feel safer (Lysaght and Basten 2003), minimizing opportunities for interaction with members of the other community. Residents might travel through out-group areas in a vehicle to reach neutral spaces such as retail parks or supermarkets, sometimes referred to as nonspaces, which have no past history of ownership or conflict (Huck et al. 2019). The bubble effect of a vehicle does not, however, appear to extend into T-communities. This is perhaps to be expected, because T-communities are rarely used as thoroughfares and therefore are unlikely to be passed through in a vehicle en route to other destinations. It should also be remembered that very little movement was recorded within out-group T-communities and limited conclusions can therefore be made in relation to travel mode within out-group T-communities.

Despite anecdotal evidence from earlier literature (Dowler 2001; Bairner and Shirlow 2003; Lysaght and Basten 2003) suggesting that women might experience greater mobility within out-group areas, evidence from the tracking data both along main roads and within T-communities in north Belfast suggests that this is not the case, with no significant difference found in the amount of time that men and women spend moving within out-group areas. Anecdotal evidence within the literature is now dated and mobility patterns could have since changed in postconflict Belfast. It is also possible that although women might be more prepared to enter out-group areas—for example, to access certain shops, services, or activities—these visits might be infrequent and hence were not fully captured within the limited time frame of the tracking data collected. An alternative explanation could be that although women typically feel less afraid of entering out-group areas, both women and men will equally prefer in-group areas, unless there is a particular need to cross a sectarian boundary.

Grannis's (1998) definition of T-communities was designed to work for large cities in the United States and thus needed scaling, through redefining the interpretation of main roads, to be applicable in this research context. This rescaling was effective in delineating boundaries that fit well with existing understanding of community divides within north Belfast and shows potential as a means of neighborhood delineation for other studies and geographic contexts. Although in some cases our T-communities extended over an area known locally to be defined by name as more than one neighborhood, these were neighborhoods of the same community affiliation and evidence from the tracking data in this area suggests that residents move throughout the whole of that T-community, not only the locally named area in which they live. Although this might suggest that T-communities do not necessarily delineate neighborhoods as recognized locally, they do represent opportunities for interaction, as originally intended by Grannis (1998). Kwan (2012) previously commented that an individual's perceived neighborhood might differ both from administratively defined neighborhoods and from people's activity spaces. In this context, our T-communities not only appear appropriate for the context studied but also offer a more meaningful fit to known community boundaries than census zones that are often used in segregation studies (Lloyd and Shuttleworth 2012; Palmer et al. 2013).

The other key adaptation to Grannis's (1998) original T-community concept was the treatment of main roads. In an area such as north Belfast, where the main roads are walkable and fronted by many residential properties, these cannot simply be excluded from the analysis. The ability to compare patterns of segregation and mobility between main road sections and T-communities proved highly beneficial, leading to a greater understanding of the types of space in which the greatest impact of segregation on mobility occurs. Because T-communities are based on real-world geographies, they provide a useful unit of assessment for real-world interventions to encourage greater mixing.

One of the key elements to understanding the impact of segregation on mobility is the GPS tracking data available for this study. This is a unique data set, obtained from a year-long field campaign (Hocking et al. 2019) representing up to two weeks of movements for 184 residents. Although the GPS tracks represent only a sample of the population for a limited time, they provide a rich source of understanding in terms of the types of spaces within which residents regularly move. The GPS data can only tell us where people do go, however, and do not offer conclusive evidence of where people do not go. Grannis's (1998) analysis of segregation was limited to residential data for census blocks, with no available information on time spent in different T-communities. The GPS track data collected for this study, however, gave us the opportunity to explore in more depth the extent to which individuals move with different types of T-communities or main roads and thus the extent to which segregation affects movement. Importantly, it also helps identify the types of spaces where opposing communities might interact. The GPS tracking data offer the opportunity to identify specific areas where greater mixing appears to occur. The most striking example of this is evident in Figure 8, at Location B. One reason for this mixing might be the location of the Belfast Royal Academy grammar school, although timing within the track data suggests that this cannot be the only explanation. Another explanation might be the lack of alternative options for local convenience shops within the neighboring Protestant community. Although the tracking data cannot confirm the full extent of or reasons for mixing occurring in this area, they do suggest that this area warrants further exploration to ascertain the extent of this mixing and what factors might be encouraging this to occur. Further examination of this mixing could enhance opportunities to encourage further interaction between the communities both here and elsewhere.

The methods developed here not only are useful for the understanding of segregation in the context of north Belfast but show the usefulness and adaptability of the T-community concept for understanding segregation and mobility in other geographic contexts.

Conclusion

This article explores the impact of segregation in new ways. A rich set of GPS tracks obtained through an extensive, year-long field study (Hocking et al. 2019) enabled us to shift analytic focus away from residential segregation, which is already relatively well understood within Northern Ireland, and toward an understanding of the impact of segregation on individuals' everyday movements. More specifically, we have argued that shifting focus away from use of administrative geographies (e.g., census boundaries) toward use of defined T-communities provides a more meaningful set of boundaries in relation to the geography that residents encounter when making day-to-day mobility choices in the city. Analysis using T-communities also enabled us to develop a clearer understanding of the different impacts that segregation has within networks of residential tertiary streets, more easily avoidable by members of the out-group community, compared to main roads, sometimes unavoidably used to access facilities elsewhere.

We have shown Grannis's (1998) T-community concept to be scalable and applicable within north Belfast. First, although the T-communities we generated were smaller in geographic area than Grannis's (1998) original work in larger cities such as Los Angeles, they are equally useful and appropriate for the street and neighborhood configurations found in Belfast. In adapting the T-community definition to fit a new geographic context, we demonstrate its flexibility to be adapted and applied in future studies elsewhere. Future work could incorporate participatory approaches (Huck et al. 2019) to defining community affiliation of T-communities. Second, within north Belfast it is clear not only that segregation occurs and affects mobility but also that the impact of segregation on mobility appears to be greatest within tertiary street networks, where movement within out-group communities is minimal. Even along main roads where greater mixing occurs, evidence suggests that most of these movements are within vehicles, thus providing rare opportunities for face-to-face interactions between members of different community groups.

In summary, it is clear that the two main communities in North Belfast remain largely disconnected from each other, almost never entering residential T-communities associated with the other community. Although there is some evidence to suggest potential connections along main roads, even here this is mostly within vehicles, thus limiting opportunities for interaction and leaving the communities disconnected from each other. More positively, however, results from our GPS tracking highlight some areas where greater mixing appears to occur, and these areas warrant further investigation. Understanding why mixing occurs in particular areas could lead to greater understanding that can in turn influence policy and planning elsewhere in the city.

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Supplemental Material

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ORCID

Gemma Davies http://orcid.org/0000-0002-7420-2479
J. Duncan Whyatt http://orcid.org/0000-0001-9329-4367
Jonny J. Huck http://orcid.org/0000-0003-4295-3646
Brendan Sturgeon http://orcid.org/0000-0001-9214-2740

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GEMMA DAVIES is the GIS Officer in the Lancaster Environment Centre at Lancaster University, Lancaster LA1 4YQ, UK. E-mail: gemma.davies@lancaster.ac.uk. Her research interests cover several areas of applied GIS, including food security, journey-time exposure to air pollution, and mobility.

JOHN DIXON is Professor of Psychology in the School of Psychology at the Open University, Milton Keynes MK7 6AA, UK. E-mail: john.dixon@open.ac.uk. His work focuses on the dynamics of intergroup contact, prejudice, and segregation in historically divided societies.

COLIN G. TREDOUX is Professor of Psychology at the University of Cape Town, Rondebosch, Cape Town 7701, South Africa, and Chaire d'Attractivité at Université de Toulouse, Jean Jaurés. E-mail: colin.tredoux@uct.ac.za. His research in social psychology focuses on modeling intergroup relations.

J. DUNCAN WHYATT is a Senior Lecturer in GIS in the Lancaster Environment Centre at Lancaster University, Lancaster LA1 4YQ, UK. E-mail: d.whyatt@lancaster.ac.uk. He has research interests in both the natural and social sciences.

JONNY J. HUCK is a Lecturer in Geographical Information Science in the Department of Geography at the University of Manchester, Manchester M13 9PL, UK. E-mail: jonathan.huck@manchester.ac.uk. His research interests include the representation of vague entities in geographical information science and the application of emergent technologies to geographical problems, particularly in the context of health and postconflict societies.

BRENDAN STURGEON is a researcher at the Institute for Conflict Research, Belfast BT15 2GG, Northern Ireland. E-mail: b.sturgeon@conflictresearch.org.uk. His research interests include segregation and policing in postconflict societies.

BREE T. HOCKING was until recently a Research Associate in the School of Psychology at The Open University, Belfast BT1 3GN, Northern Ireland. E-mail: breehocking@hotmail.com. An independent scholar and writer, her work focuses on spatial politics, identity, public art, and the anthropology of tourism in postindustrial and postconflict landscapes.

NEIL JARMAN is Director of the Institute for Conflict Research, Belfast BT15 2GG, Northern Ireland. E-mail: n.jarman@conflictresearch.org.uk. His research focuses on such issues as street violence, disputes over parades, management of public order, police reform, racist and homophobic violence, and human rights in a number of countries, including Northern Ireland, South Africa, the United States, Israel and Palestine, Kosovo, and Nepal.

DOMINIC BRYAN is a Reader in Anthropology in the Institute of Irish Studies at Queen's University Belfast, Belfast BT7 1NN, Northern Ireland. E-mail: d.bryan@qub.ac.uk. His research interests include the politics of rituals and symbols in Northern Ireland and other divided societies.