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Agent based modeling of population dynamics in municipalities: Migration in the Derbyshire & Nottinghamshire cases in the UK.

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Executive summary

An agent-based model was developed to study migration dynamics. The model is capable of simulating a population with agents that make a decision to migrate or not. Economic, social and environmental satisfaction are the key drivers of migration. Jobs deliver economic satisfaction, the number of friends living close determines social satisfaction, and the quality of the environment determines environmental satisfaction. Agents are connected in a similarity based network, and can share information.

The simulation model is applied to Derbyshire & Nottinghamshire in the UK, including 14 wards, which is a low-level election unit in UK. A population of 58.000 agents is initialized reflecting age, income, qualification (education) and social professional status (working status) in the area. Data for this initialization originate from various sources including UK Census 2001, neighborhood statistics, and so on. An individual's working status can be either *student, worker, unemployed, retired* or *inactive*. For those individuals whose working status is 'worker', information is generated about their *Socio Professional Category* (6 categories), *sector of activity* (10 categories), such as Agriculture-Forestry-Fisheries, Communications, Construction, and so on; *working location* (an agent living in the focusing area of study can work within a list of 219 wards, based on census data)*;* and the *commuting distance* (as the distance between a worker's residence ward and working ward). Furthermore, we generate individual's qualification level and income, including pensions for retiree, benefits for unemployed, and so on.

Running the UK adaptation of the agent-based model shows how the population changes, and in the figure we can observe for two wards how the population of different categories of people changes over time. Also we can see the strong difference between the presence (full line) of absence (dotted line) of the social need on in particular the workers (green) decision to migrate. It can be seen that the workers population decreases the most.

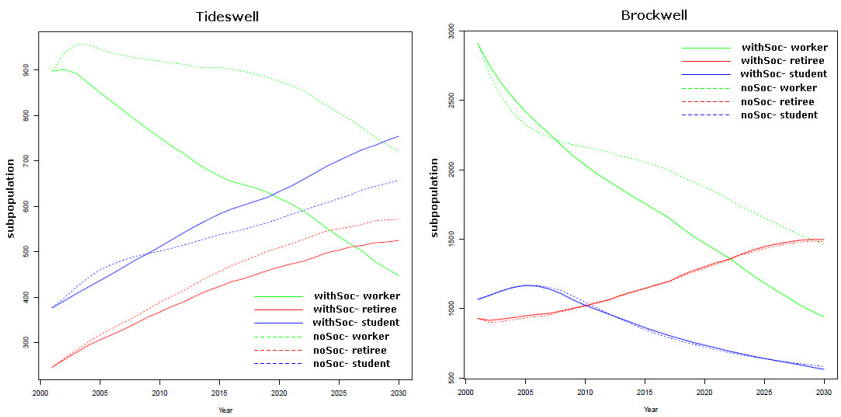


Figure: Evolution of Agent-Based model Simulation, example of two wards

The experiments demonstrate that in particular social needs may have a strong impact on population dynamics. Most interestingly is that in the context of a declining population the presence of a social need causes the population to initially decrease at a slower rate because of their social satisfaction (stabilizing effect). However, if a critical population size is reached, the social satisfaction decreases, and causes more people to move, resulting in a self-amplifying dynamical process. This is typically what happens in the ward of Brockwell, and we observed this in other wards dealing with a substantial population decline as well.

For the policy maker the question thus is how to anticipate such a sudden population decline and how to prevent it, if possible and desired. The empirically parameterized model we developed allows having a deeper look at the attributes of the agents that are moving away. This makes it possible to make more fine-grained projections of what type of people are more likely to move away, and for what reasons. Looking at the population dynamics for different categories of inhabitants of Brockwell (right hand figure) one sees a strong decline in the workers, a smaller decline in the students, and an increase in the population of retirees. For the policy maker such simulated projections may support strategic decision making. For example, the policy maker first may try to develop a strategy to avoid existing workers and their children (students) leaving the ward. This would probably require the creation of jobs. The model allows for exploring how creating jobs in different socio professional categories and sectors of activity may match with the qualification of the agents that are prone to move. It would also be possible to explore if the qualifications of workers would match with an increased demand for services of the retirees that move to the ward. Retirees are attracted to the area, probably because of the environmental quality. If this is good for the vitality of the ward, policy makers may consider possibilities to stimulate this. Ideally this may result in a strategy to create jobs around servicing retired people, thus making the ward more attractive for all groups. Hence one can imagine that investments in particular activities and services in which retirees are interested would benefit the population at large.

Obviously the precise strategies cannot be derived from the simulation model, but this downscaling of population dynamics using an agent based model illustrates the possibilities of identifying the possible developments in the system at a detailed level, which in turn is helping to focus the policy making effort at potential effective policies at the specific ward level. This level also fits well with the scale of EU community funding policies aimed at supporting the viability of mainly depopulating agricultural areas in Europe. Having a simulation tool that is capable of exploring the population dynamics at the same level as the policies that are implemented opens a perspective on developing more effective policies, and possibly on testing policies using the same simulation tool.

1. Introduction

Mankind has always moved from one spot to another in trying to find a better place to live. In ancient times large migrations of tribes and complete populations happened, and also in our times large migration streams are related to escaping from poverty, war and repression. On a smaller and less dramatic scale such migrations can be observed in many areas. Whereas in some areas the in and out migration are balancing each other out, other areas deal with problems of large immigration or emigration. In particular the European Union recognizes that many areas within Europe are facing problems related to emigration, resulting in a decrease of the population, and a reduced quality of life for the people that stay. For example, several rural areas in Europe face an outmigration of younger people that study in the larger cities, and pursue a career over there. This results in a decrease of the original population, but also in a shift of the population towards an older and less educated population. The resulting decrease in "vitality" in such communities may further decrease the attractiveness of such communities. In some cases there is even mentioning of "ghost towns", where only a few elderly inhabitants remain.

In stimulating the vitality of communities facing problems of depopulation, the EU supports local projects aimed at creating new job opportunities. The basic idea here is that creating new jobs, preferably also for high qualified people, might increase the attractiveness of the community, and thus the vitality of local communities may be protected or even restored by such projects. However, besides the importance of economic factors, also other factors may have an impact on the people's decision to stay or go. The "social vitality" of a community is expected to be a relevant factor, as if a person has a lot of social connections in a community (family, friends), this may stimulate this person to stay, and possibly accept a job with lower wages. However, if this social cohesion drops because many friends and family members emigrate, the step to migrate oneself is becoming easier to take. In the same vein, if an interesting job becomes available in a community, the lack of social cohesiveness may have a negative impact on ones interest for that job. Hence, while acknowledging the importance of the availability of jobs for the 'vitality' of a community, this social dimension may have an important impact as well.

Whereas the availability of jobs can to a certain extent be influenced by policy, e.g. special EU projects, this social cohesion is a factor that cannot be influenced directly. Moreover, because the social cohesion is dependant on the connectivity of the inhabitants, it is an emergent property of the community. This implies that a strong social cohesion may function as a barrier towards large emigration, but once the social cohesion drops due to large migration, it is very difficult to reverse this situation as social cohesion is difficult to restore.

Yet another factor that is expected to be important in emigration and immigration issues is the environmental quality of the area in question. This environmental quality is a

broad concept, related to both natural and man-made properties of the environment, such as the beauty of the landscape, possibilities for leisure activities, the architectural quality of a community and the like. It can be expected that a community situated in a high quality – and thus expensive - environment but with low employment is more attractive for pensioners having a good income, whereas young people pursuing a career have less opportunity to find an acceptable means of living in such a community. Whereas policy has a limited influence on environmental quality, e.g. by investing in opportunities for leisure or investment in the built environment (e.g., restoration of historical sites, new housing), it has to be acknowledged that this factor may translate in the prices of housing, which is subject to the free market.

Policy makers have increasingly realized the importance of taking into account well-being in their policy making (new rural paradigm, OECD 2006). The challenges for policy makers to include well-being and quality of life into their considerations are manifold. First, as discussed above, evaluation of life quality consists of multiple dimensions and varies between individuals. Second, individuals' decisions are interrelated, as people share information and exert normative influences on each other. For example, family ties and friend ties are determinants to migration decisions. Third, interdependencies between people and/or households have a geographical component. Whereas often people prefer to work in close proximity to their social environment, it is common that individuals live and work in different municipalities. Here one municipality may provide better job opportunities (economic motive), whereas another municipality offers better social and environmental quality (or cheaper housing), and commuting becomes a strategy to increase quality of life. However, if the commuting distance becomes large this may have a negative impact on the quality of life. This indicates that policy should not focus on single municipalities, but rather study a region as a collective of municipalities each offering different qualities.

Because part of the quality of life of people is dependant on the decisions of other community members (e.g. family and friends moving away), the social influences that affect individuals' decision making and the interrelation of developments in nearby municipalities, the migration behavior in a region can be considered to be a complex behaving phenomenon. This implies that developments in a region may take different courses due to relative small events at the micro level. For example, the migration of a single family may cause a cascade effect, causing more people to migrate and having a negative effect on the vitality of this municipality and the quality of life of the remaining residents (emergence). The evolving condition of the municipality due to such emergent effects sets the stage for the other residents in deciding to stay or to go (downward causation). In particular when such complexities arise from interactions between individuals, agent based modeling offers a tool to simulate these complexities (see e.g. Gilbert & Troitzsch, 2005), and provide insight in the possible futures of municipalities.

Several agent based models have been developed to study the dynamics of population movements, to begin with the seminal work of Schelling (1971). Much work

has been devoted to the modeling of housing markets, focusing at economic motives (e.g., Filatova *et al*, 2009, see also Parker & Filatova (2008) and Polhill, Parker & Gotts (2008) for an overview). The agent based model we present in this report deviates from previous work as it includes social and environmental outcomes in addition to economic outcomes. Hence we offer a simulation tool capable of including a multidimensional perspective on well-being, which also offers a tool to explore to what extent emergent phenomena underlie population dynamics in municipalities. This agent based model is developed within the context of the EU funded PRIMA project, which is aimed at developing a deeper understanding of the population dynamics of communities in Europe. Within this project fine grained empirical data are collected on developments in different regions of Europe[1], which are linked in a micro-simulation model of the regions, which successively support the parameterization of an agent based model of the population dynamics in municipalities within these regions. In this report we will focus on the formalization of this agent-based model, and an application for the region of Derbyshire & Nottinghamshire in the UK. First we will explain the model of the agent-based model we developed for this project. Next we will explain how the empirical data were used in parameterising the model for the selected region. Following that we will present a number of simulation runs aimed at illustrating the role of social and environmental outcomes in addition to economical outcomes, and show how an agent based model is capable of producing detailed scenarios of population dynamics which may contribute to policy development. The report will conclude with a perspective on how the model can be used in studying the population dynamics in other regions.

[1] Derbyshire & Nottinghamshire in the UK, Altmark in Germany, Auvergne in France, South Moravia in the Czech Republic, Istria in Croatia and the North Central Planning Region in Bulgaria

2: The model

The agent-based model we developed provides a generic model of individual decision making of activity change and residence change. It is based on (1) formalising a multidimensional satisfaction function based on economic, social and environmental satisfaction, and (2) formalizing a decision-making framework combining individual and social decision-making.

In this section, we will firstly describe an individual's decision making process of changing activity. An overview of the process is followed by detailed explanation on the key concepts in the process. It is mainly about the formalization of satisfaction-driven decision-making. Then, we describe the process of household's moving decision and the updating of municipalities.

Individual's decision making process of changing activity

The process describing the individual agent's ($agent_a$) decision making about changing activities is depicted in the flowchart presented in *Figure 1*. The basic principles are as follows. Suppose $agent_a$ is taking activity Act_i at time *t*. If $agent_a$ is not completely satisfied with its multiple needs (economic, social & environmental), it considers taking alternative activities (from time *t+1)*. The lower the multiple satisfaction, the larger the chance that $agent_a$ will be motivated to change activity. This translates first in its chance to update information about available activities, through asking other individuals about their experience (observe closests contacts) and/or exploring by $agent_a$ itself (look up vacancies). Based on the collected information, $agent_a$ estimates its potential satisfaction to gain from taking another activity Act_j. The higher the expected satisfaction from Act_j, the more likely that $agent_a$ will engage in that activity . Under the condition that all the requirements of taking Act_j are met, $agent_a$ will change to Act_j. In the following the different steps will be explained in detail.

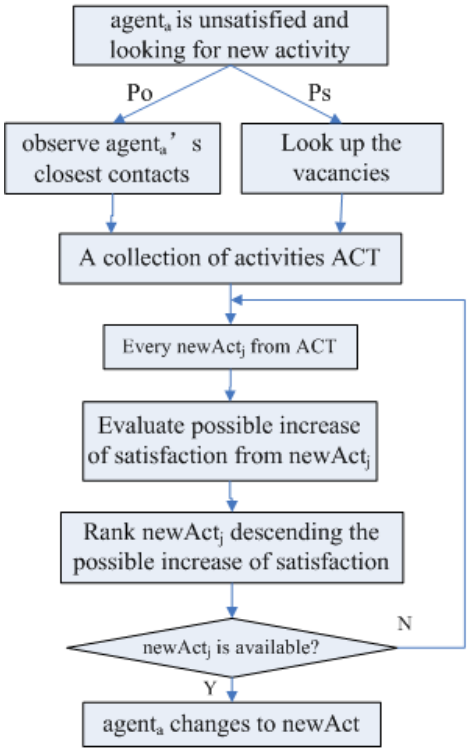


Figure 1: Flowchart of individual's decision making process

Satisfaction: individual's motivation to change activity

An individual's qualify of life (or happiness, wellbeing) is determined by its overall satisfaction on multiple needs. This model accounts for three needs, a social need, an economic need and an environmental need. Taking an activity Act_i produces certain amount of utility to satisfy each need of $agent_a$, notated as $Sat_{soc}(a)$, $Sat_{eco}(a)$, and $Sat_{env}(a)$. $agent_a$ may value different dimension of needs with certain level of importance, notated $w_{soc}(a)$, $w_{eco}(a)$, and $w_{env}(a)$. Each weight is in the range of [0,1], and $w_{soc}(a)+w_{eco}(a)+w_{env}(a)=1$. The $agent_a$'s overall satisfaction (notated Sat(a)) is the weighted sum of its satisfaction on the three needs:

$$Sat(a) = Sat_{soc}(a)* w_{soc}(a) + Sat_{eco}(a) * w_{eco}(a) + Sat_{env}(a) * w_{env}(a)$$

The weighting of needs depends on the agents socio-demographic characteristics. The parameterization of weights will be introduced in the next section. The satisfaction level of $agent_a$ concerning the three needs is based on its current state and its personal preferences concerning the attributes relevant to that need. This is formalized as $Sat_m(a)= f(P_x, R_x)$, where $_m$ represents either of social, economical and environmental dimension, P and R are respectively the state and reference points about attributes x. The needs have

different satisfaction functions $f(P_x, R_x)$. Whereas economic and social satisfaction have a "more is better" characteristic, the environmental need is more related to a personal preference. Therefore, the economic and social need are formalized according to a vector model, and the environmental need as an ideal point model.

In a *vector model* of satisfaction (shown in Figure 2), two threshold values are derived from an individual's personal preference, namely the lower bound R_{min} and upper bound R_{max}. Together they specify a range between which an individual's satisfaction is linearly increasing. If the current state P is below R_{min}, the individual is completely dissatisfied. If P is above R_{max}, the individual is completely satisfied.

$$f = \begin{cases} 0 & P \leq R_{min} \\ \dfrac{P - R_{min}}{R_{max} - R_{min}} & R_{min} < P < R_{max} \\ 1 & P \geq R_{max} \end{cases}$$

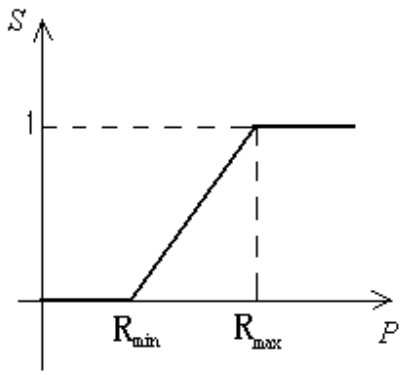


Figure 2: Formalisation of the economic and social need following a vector model.

The $agent_a$'s economical satisfaction $Sat_{eco}(a)$ and Social satisfaction $Sat_{soc}(a)$ are both following such a vector model. Economic satisfaction $Sat_{eco}(a)$ is determined by how the agent's current income is compared to $Income_{min}(a)$ and $Income_{max}(a)$, defining the personal satisfaction function of $agent_a$ concerning its economical state. Concerning social satisfaction, $Sat_{soc}(a)$ is defined as the percentage of regular contacts that live within $agent_a$'s preferable distance. That is to say, the emigration (to other municipality, region or state) of regular contacts decreases an individual's social satisfaction.

The ideal point model is used to formalize the environmental satisfaction of the agent. Here "taste" is of importance, as some people prefer to live in a crowed town, whereas others prefer the tranquility of the countryside. The ideal point model applies when $agent_a$ has in mind an ideal status that it expects to live in. The closer that the current states in reality are compared to this ideal status, the more satisfied an agent is. Similar to the

vector model, two threshold values are derived from personal preference. They specify a range beyond which $agent_a$ is completely dissatisfied (shown in Figure 3).

$$f' = \begin{cases} 1 & P = R_{ideal} \\ 0 & P \le R_{\min}, P \ge R_{\max} \\ \dfrac{P - R_{\min}}{R_{ideal} - R_{\min}} & R_{\min} < P < R_{ideal} \\ \dfrac{R_{\max} - P}{R_{\max} - R_{ideal}} & R_{ideal} < P < R_{\max} \end{cases}$$

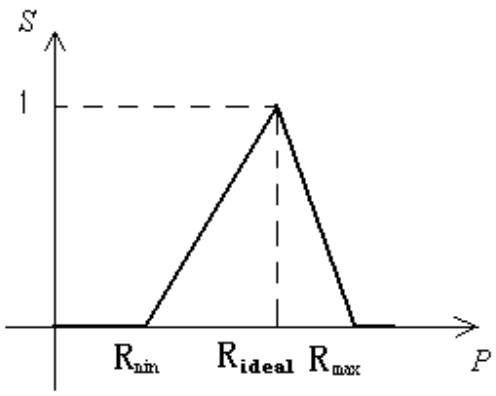


Figure 3: Formalisation of the environmental need following an ideal point model

Environmental satisfaction $Sat_{env}(a)$ expresses how satisfied an agent is with living in a municipality, and can be used to calculate its expected social satisfaction when moving to another municipality. To measure the current state of a municipality, we use the average housing price as a proxy. It can be expected that the price of houses expresses people's valuation of a certain environment, and price is capable as a single indicator that allows for a direct comparison of environmental satisfaction both on in the he countryside as in the city, because both in rural and urban areas large price differences exists which can be related to environmental quality. Using price as a proxy avoids very complicated evaluation procedures to formalize environmental quality.

Updating information about alternative activities

A completely satisfied individual is not motivated to make any change. The more satisfaction decreases, in particular of the need that is weighted as most important, the more a person will become motivated to change activity. For example, a better-paid job is more likely to be accepted by someone that currently has an unsatisfactory income than by someone that is satisfied with its income. If the job requires relocation this will be

more feasible for a person attaching more weight to the economic need than for someone attaching more weight to the social need and that is very satisfied with living close to family and friends. It is also common that a person is willing to pay a high price to live in a pleasant neighborhood. The fact that higher environmental satisfaction is gained at the cost of lower economical satisfaction can be explained by the higher importance he/she values environmental need than economical need.

In the model this is formalized in the rules for the agents. In order to make a decision about changing activity, $agent_a$ needs to update information about the currently available activities. If $agent_a$ is very dissatisfied, in particular with respect to the most heavily weighted need(s), it will be very active in collecting information about alternative activities. The frequency with which $agent_a$ updates information is represented by the following equation:

$$P_{update\_info}(a) = (1\text{-}Sat_{soc}(a))* w_{soc}(a) + (1\text{-}Sat_{eco}(a)) * w_{eco}(a) + (1\text{-}Sat_{env}(a)) * w_{env}(a)$$

$P_{update\_info}(a)$ ranges between [0,1], 0 expressing a fully satisfied agent not updating at all, and 1 expressing a dissatisfied agent that updates every time-step.

A main distinction in information processing is between social and individual information processing. Social processing implies observing the actions of others or asking about their experiences. Individual processing implies exploring opportunities on one's own, e.g. looking for vacancies. People vary in their preference about how to obtain information. Some rely more on the experiences of other people, whereas others are more likely explore by themselves. The innovation diffusion theory of Rogers (1983) states for example that innovators are more likely to follow individualistic strategies, which is obvious because innovation does not come from following other people. Innovators are more risk-prone, younger, more often belong to a higher social class, have more money, more social contacts and more knowledge. Hence in the model it is essential distinguishing between social and individual processing. P_{ask} represents the chances that an individual asks others for information - thus engaging in social processing - when it updates information for decision of changing activity. If P_{ask}=1, an individual completely relies on asking others to get information. It has little chance noticing those activities that are rarely taken by others, in particular the newly available activities. On the other hand, individual processing, which demands higher cognitive abilities and efforts, enables an individual to access opportunities that are innovative to the community. Especially innovative agents may stimulate new behaviours to spread faster and to a larger degree through a society (e.g. Van Eck, Jager & Leeflang, 2011).

In modeling social processing, we follow the principles of similarity or homophily, theory, stating that people are more likely to interact with similar others (e.g. McPherson, Smith-Lovin & Cook, 2001). If $agent_a$ gets information from others, the chances that $agent_a$ asks another $agent_b$ ($C_{a,b}$) is proportional to the similarity between $agent_a$ and $agent_b$. Many factors can be used to define similarity, and the implementation of the

model will be discussed in detail in the section on implementation.

Willingness of changing activity

Based on the updated information, an individual estimates how much more satisfaction it may gain through taking a specific activity. The more an individual predicts to increase its need satisfaction from an activity, the more it is willing to take that activity. If an agent engages in social processing, the willingness of following the same activity is proportional to the difference of two individuals' satisfaction, as captured in the following equation:

$P_{a,b} = (Sat_{soc}(b)-Sat_{soc}(a)) * w_{soc}(a) + (Sat_{eco}(b)-Sat_{eco}(a)) * w_{eco}(a) + (Sat_{env}(b)-Sat_{env}(a)) * w_{env}(a)$

If $P_{a,b}>0$, then $agent_a$'s interest of adopting $agent_b$'s activity (supposing Actj) is:

$P_{Actj} = P_{update\_info}(a) * P_{ask}*C_{a,b} *P_{a,b}$.

$C_{a,b}$ (from equation 1) is the chances that $agent_a$ gets information from $agent_b$. Remind that $C_{a,b}$ measures the similarity between $agent_a$ and $agent_b$. This captures the idea that when an individual asks others having similar abilities and opinions, the chances of obtaining relevant information on feasible activities is larger.

If an agent engages in individual processing, estimating the increasing satisfaction is based on the information collected about the activity, mainly related to the potentially new income, working location, and living location. This determines $agent_a$'s willingness of changing to a new activity (supposing Actj) as:

$P_{change} = (Sat_{soc}(a)'-Sat_{soc}(a)) * w_{soc}(a) + (Sat_{eco}(a)'-Sat_{eco}(a)) * w_{eco}(a) + (Sat_{env}(a)' - Sat_{env}(a)) * w_{env}(a)$,

where $Sat_{soc}(a)'$, $Sat_{eco}(a)'$ and $Sat_{env}(a)'$ are estimated satisfaction from taking Actj.

Then $agent_a$'s interest of changing to Actj is:

$P_{Actj} = P_{update\_info}(a) * (1-P_{ask}) *P_{change}$.

Feasibility check

An individual can change for an activity Act_j only if the following conditions are met. Firstly, there is opening of Act_j (of specified sector, specified social-professional category, in specific working location). Secondly, an individual meets the requirements of the Act_j. These conditions are met automatically if an agent engages in individual processing, as it

is selecting opportunities that are feasible. However, in the case of social processing this feasibility check is necessary if because the information originates from other agents with possibly different qualifications. This is formalized as a simple requirement: if the qualification of an agent is equal or larger than the qualification of the agent providing the information about the activity, this activity is considered to be feasible.

Household's decision making of changing residence

A household starts a decision-making process about moving if any household member is interested in moving outside the municipality where they are currently living. While an individual household member's motivation to move is related to its expected increase in need satisfaction, whether to move and where to move has to be a collective decision made by all the household members. This is because for some household members a new residence location may imply an unacceptable commuting distance. Hence there are two objectives in the decision-making process of the household. The first is to avoid an unbearable commuting distance to any workers in the household. The second is to find an optimal location (among proposed options by the household members) that satisfies all the members the most.

Updating of municipalities

Following the decisions and possible activity changes of individuals and households, every municipality will update its status concerning population size, job availability and housing stock.

3. Implementation

In order to test the agent based model, we needed to focus on a region to target. In the PRIMA project several regions in the EU were studied. We decided to focus on the region of Derbyshire & Nottinghamshire in the UK because (1) this region faced the situation of a population decline, and (2) the availability of many data that could be used in parameterising the model. In this section, we describe how the model is adapted to a case study in UK. The focus is on how field data, empirical evidence, and theoretical-grounded constructions are integrated in the agent based model.

Agent population

As a first step we have to construct a population of 54.885 agents that reflects the population in the area of the case study. For this we used data on age, income, qualification (education) and social professional status (working status). Data were provided by **The study focuses at an area in Derbyshire & Nottinghamshire including 14 wards, which is a low-level election unit in UK. Using a stochastic method, individuals living in these wards are generated along with their initial activities (jobs). Data for this initialization originate from various sources including UK Census 2001, neighborhood statistics, and so on.

An individual's working status can be either *student, worker, unemployed, retired* or *inactive*. For those individuals whose working status is 'worker', information is generated about their *Socio Professional Category* (6 categories), *sector of activity* (10 categories), such including Agriculture-Forestry-Fisheries, Mining, Manufacturing, transport-Construction, Wholesale-retail, Hotel-restaurant, Financial-business, Public and others, *working location* (an agent living in the focusing area of study can work within a list of 219 wards, based on census data)*;* and the *commuting distance* (as the distance between a worker's residence ward and working ward). Furthermore, we generate individual's qualification level and income, including pensions for retiree, benefits for unemployed and income for students. Table 3 in the appendix provides an overview of the state variables of ward, household, and agents.

Agents' satisfaction functions

In order to calculate the agent's individual satisfaction levels, two groups of parameters need to be specified:

(1) Reference points. As mentioned, threshold values in social satisfaction ($Pro_{min}(a)$, $Pro_{max}(a)$), in economical satisfaction ($Income_{min}(a)$, $Income_{max}(a)$), and environmental satisfaction ($Env_{min}(a)$, $Env_{ideal}(a)$, $Env_{max}(a)$) have to be defined to formalize the levels at which agents are satisfied with a certain outcome.

(2) Personal preference. Wsoc, Weco, Wenv are respectively the weights that $agent_a$ values each dimension of need. This allows formalizing heterogeneity in agents

concerning the relative importance of economic, social and environmental outcomes on their over-all satisfaction level.

In this version of model, the parameterisation of these values is generated and normally distributed in the population. In further application of this model, we suggest conducting a survey on the population to be modelled in order to get a sample of personal preferences, which are hypothesized to associate with socio-demographic characteristics, such as age, activity sector, education level.

Agents' social network

Because agents influence each other, both by sharing information as by contributing to social satisfaction, a network has to be constructed that connects the agents in our model. Whereas often random networks are used in this context, theoretical notions on networks emphasize the importance of homophily (similarity) as a key factor increasing the likelihood of being connected. The customers' social network affects with whom customers communicate. Whether customers talk with specific members in their social network strongly depends on the strength of their relation (tie strength), the similarity between the two customers (homophily) and, the position customers have in their network and the role the customers play within their network, (e.g., Rogers, 1983; Brown & Reingen, 1987; Ryu & Feick, 2007; McPherson, Smith-Lovin, & Cook, 2001).

Two procedures are needed to construct the social network of individual agents. The first is to initialize a network for each agent consisting of a number of contacts that an individual is most likely to interact with, namely, its 'regular contacts'. This first procedure results in a fixed network that can be used in the simulation experiments. However, it should be realized that when an agent changes its activity, e.g. changing of job and/or moving to another ward, the social context may change. Hence the network can also be formalized as a dynamic system, where changes in activity have an impact on similarity, and translate in a rearrangement of the social network. This second procedure concerns updating an individual's regular contacts as their activities and residence may change over time.

Procedure 1: Initialization of individual's regular contacts

In the model, the chances of $agent_a$ to interact with $agent_b$ depends to the extent $agent_b$:

- is a family member of $agent_a$'s. (familyW(a,b)),
- is a neighbour of $agent_a$'s (neighbourW(a,b)). Two households living in the same ward with similar total household income are considered more likely to be neighbours.
- has the same working status, similar working location, and similar sector of activity as $agent_a$ (workStatusSimW + soaSimW + workWardSimW)

Table 1 provides an overview of the variables determining the chances of interacting.

Table 1. Measurement of interaction possibility

Aspect	**Value**
familyW	0
	1(belong to the same household)
neighborW	0
	1(are neighbours)
workStatusSimW	0
	1(if both are worker /student/ unemployed/ retired/ inactive)
soaSimW	0
	1(workers of the same sector of activity)
workWardSimW	0
	1(workers of same work ward or non-workers of the same residence ward)

The chances that $agent_b$ may interact with $agent_a$ is formalised as:

Interact(a,b)=familyW(a,b)+neighborW(a,b)+(workStatusSim(a,b)+(soaSim(a,b)+ workWardSimW(a,b)).

If (Interact(a,b) > 0), $agent_b$ is in $agent_a$'s network.

- Measure similarity

Similarity between agents is postulated to increase social influence, and is formalized as the difference on four attributes: age, income, qualification and social professional category. The smaller this composed difference is, the larger the similarity between agents. The closer two individuals' status is, the more similar they are, and the stronger their connection is. In Table 2 the variables being used to determine similarity are presented.

Table 2. Measurement of similarity to determine the influence

Aspect	**Value**
ageSimW	(1, 0.75, 0.5, 0.25) if $agent_a$ and $agent_b$'s age difference is within (5, 10, 15, 20) years.
incomeSimW, qualificationSimW, spcSimW;	(1, 0.5, 0.25) if the difference between $agent_a$ and $agent_b$'s state (either income level, qualification, or social professional category is within (0, 1, 2) levels)

For every $agent_b$ in $agent_a$'s network, similarity between $agent_a$ and $agent_b$ is:

Sim(a,b) = ageSimW + incomeSimW + qualificationSimW + socialProfessionalCategorySimW

- Select influential connections.

Rank Sim(a,b) of $agent_a$'s regular contacts. The first 20 contacts with the highest connection weights are considered the most similar references of $agent_a$'s. This number is smaller than the frequently mentioned Dunbar number of 150 contacts (Dunbar, 1998), however, the number of contacts one can maintain is obvious larger than the number of contact that are really influential. Setting the number at 20 still allows a large number of contacts to have influence, yet it is computational much less demanding than having 150 contacts.

Procedure 2: Updates of individuals' network

As time passes by, an individual and its regular contacts may change activities, residence, and other status variables. As a result, a connection may strengthen or decay along time. For example, workers who have changed activities add new connections and may reselect influential contacts depending on the similarity. This activity change obviously also affects the relation with the existing connected agents whose states have not changed.

4: Results

In this section, we report and discuss experiment results using a baseline scenario. This baseline scenario is the empirical-based setup using data from 2001 which includes (1) agent population, (2) job vacancies and residence vacancies, in each ward. Initial vacancies are fixed for all the simulation runs. There are no externally created jobs or residences after a simulation starts. In other words, both job positions and residence places are fixed for each ward throughout a simulation. One simulation covers the period of 30 years, i.e., from 2001 to 2030. We have three main objectives in experimenting with the model. The results will be shown in three parts to meet these objectives. First, we demonstrate that the model can capture dynamic and complex developments, particularly at lower geographical level. Second, we aim to study the effect of social need on the population development by comparing simulation outcomes in two conditions: (1) the individual agent has an economic an environmental need, but no social need (notated as noSocial), and (2) the individual agent has social, economic, and environmental needs. Its social contacts are fixed through the simulation (notated as staSocial). Third, we also study the effect of a dynamically changing social network on the population development. Comparing runs under condition (2) with condition (3) allow for testing the effect of adding dynamical change in the social network structure on the population dynamics. Changes in agents' job and residence may lead to updates in the social network connecting agents (notated as dynSocial). We have run three sets of simulation experiments. In each set of experiments, all the agents are specified with one of above three conditions.

Overall results of population change

The development of the population aggregated over the 14 wards where the agents initially live is depicted in Figure 4. The dotted line is when agents have economical need and environmental need but no social need affecting their decision making; the solid line shows results from the social condition when individual agent has social need and fixed social contacts throughout the simulation; and the dashed line is when agents have social satisfaction and their social contacts update if applicable. Comparing year 2030 and 2001, in all three conditions, population has decreased at least around 12500 (in noSocial condition) and about 15000 (in staSocial and dynSocial condition).

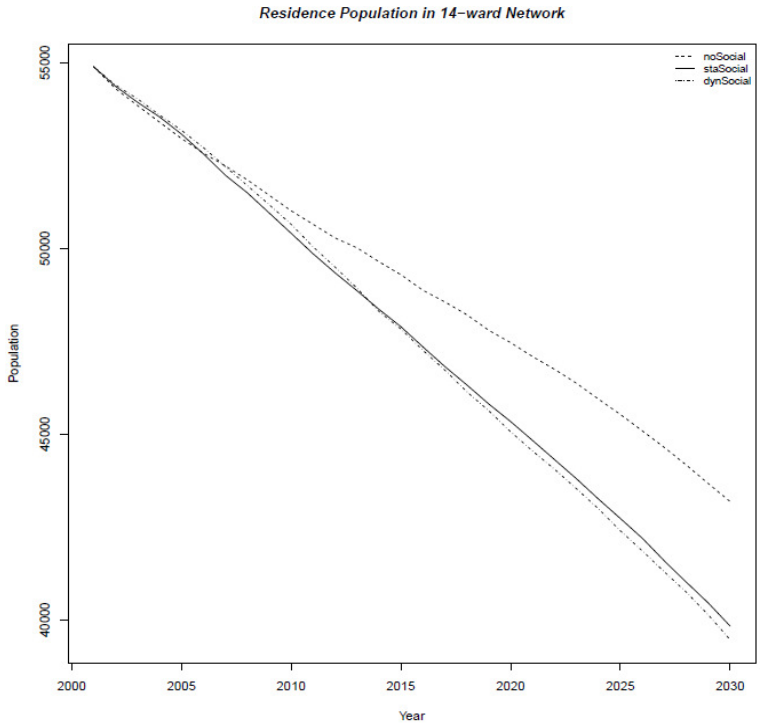
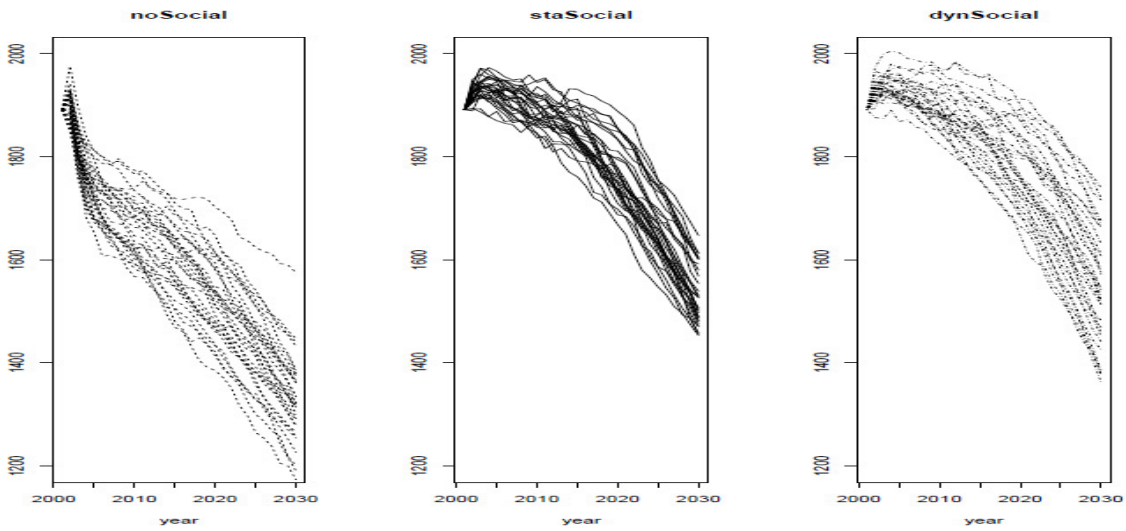


Figure 4: Population change observed at aggregated (14-ward) level

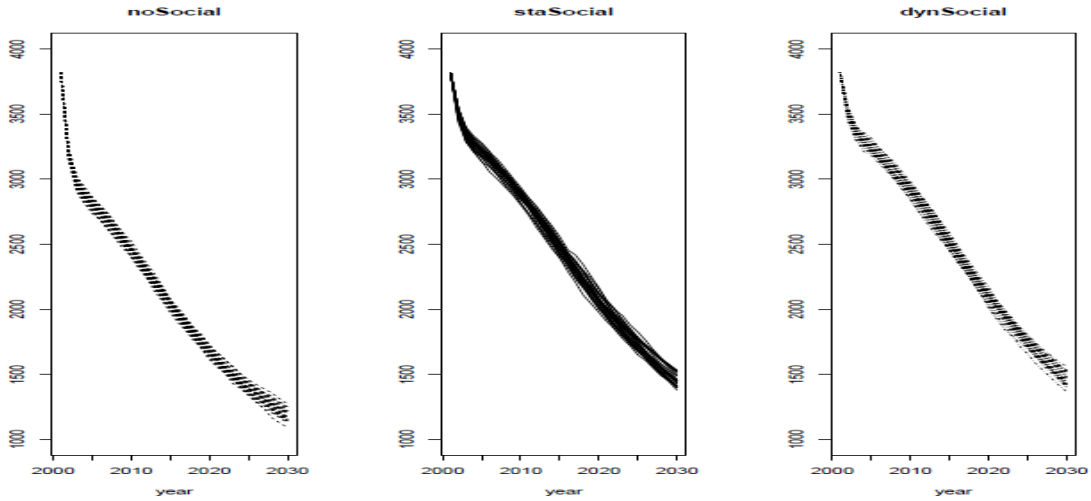
In Figure 4 it can be seen that the population decline is larger when social need are included in agent model, which is confirmed by an ANOVA test (F=2367.035, df=1, p<.05).

Zooming in, we show in Figure 5 the population developments in each ward from individual runs of simulation in noSocial, staSocial, and dynSocial condition.

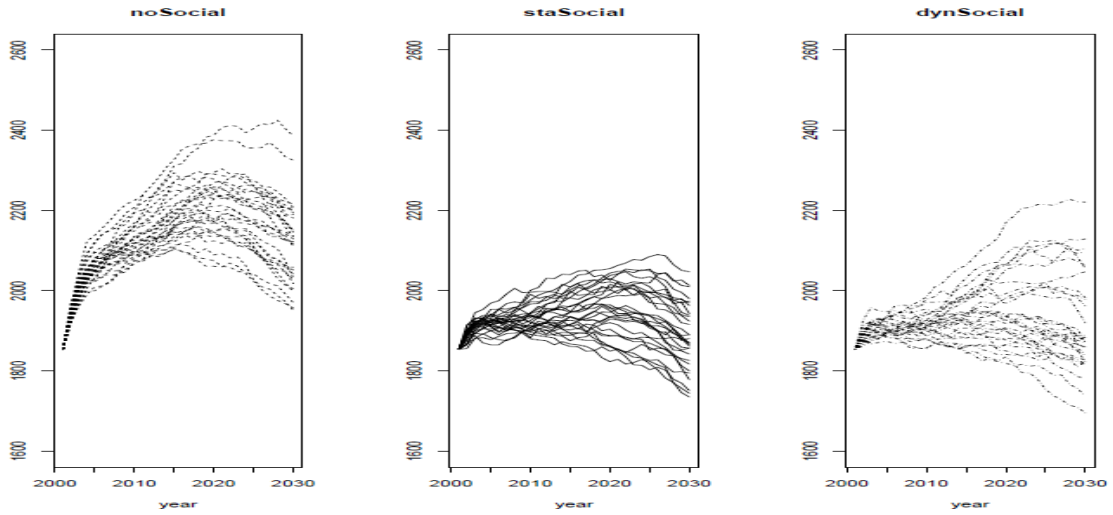
Bradwell



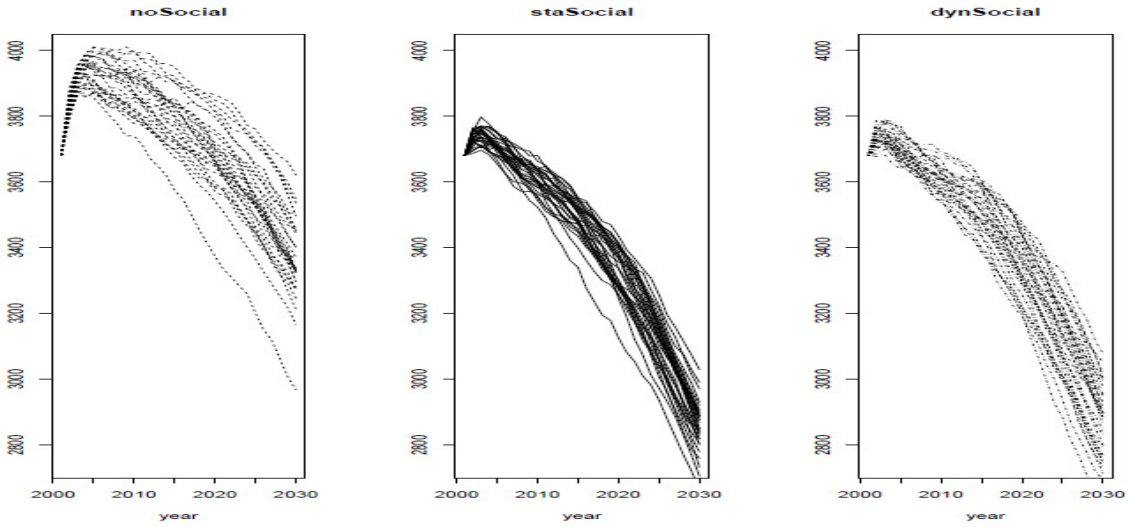
HopeValley



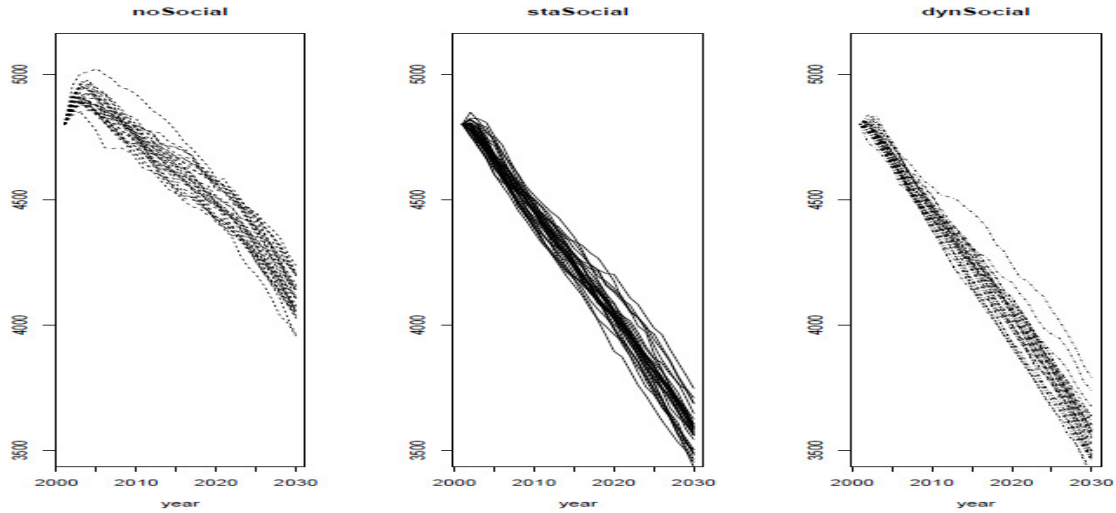
Tideswell



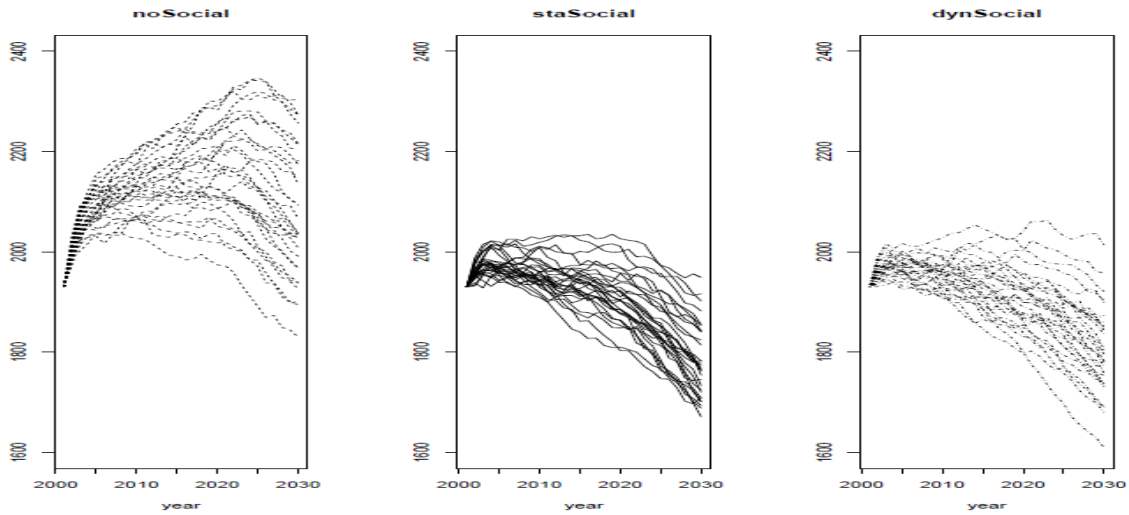
HathersageEyam



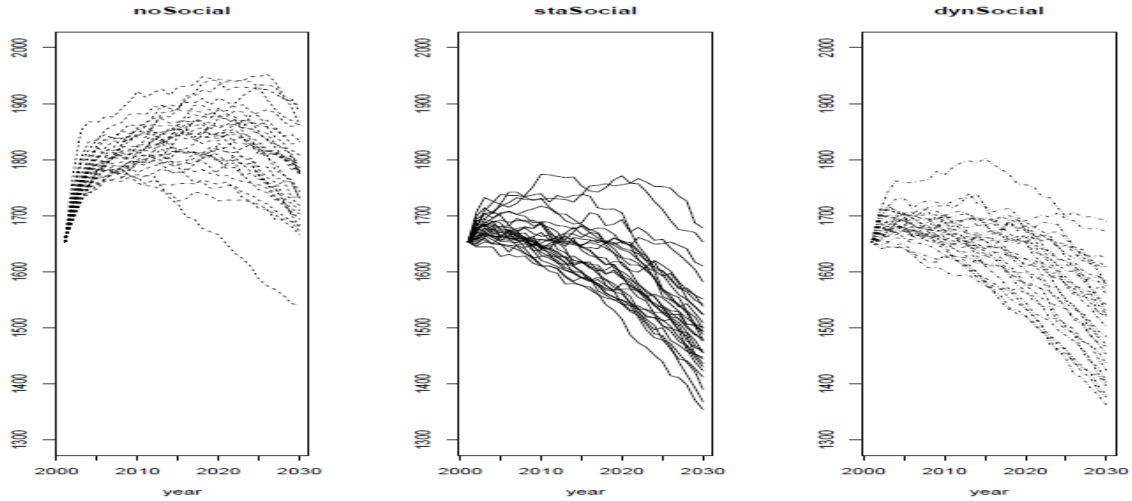
Bakewell



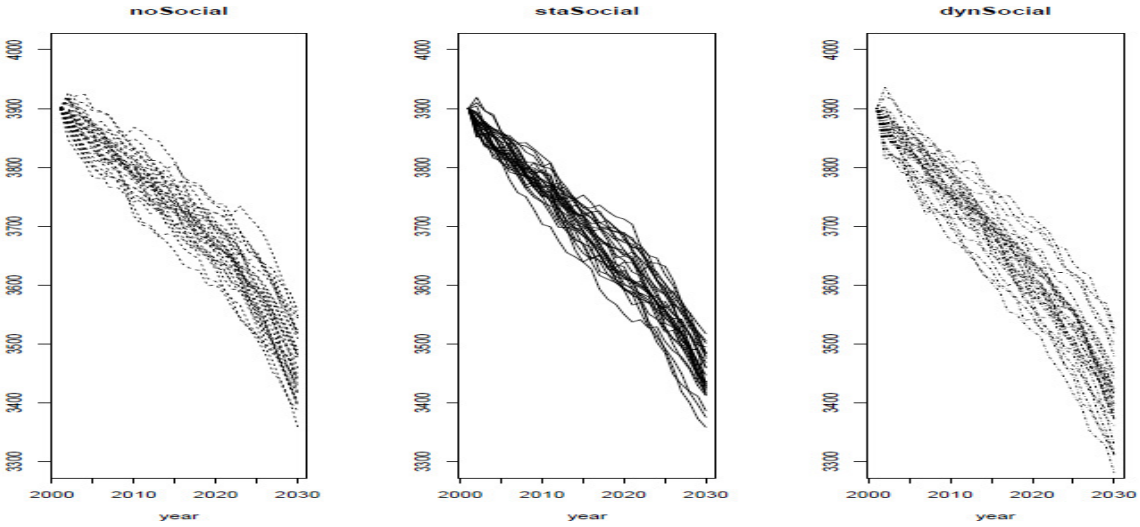
Calver



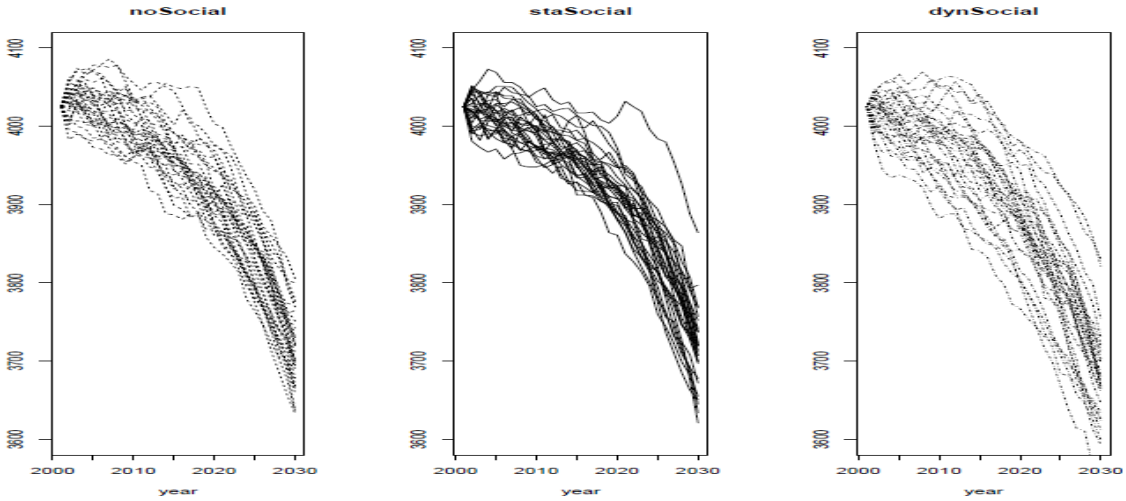
LittonLongstone



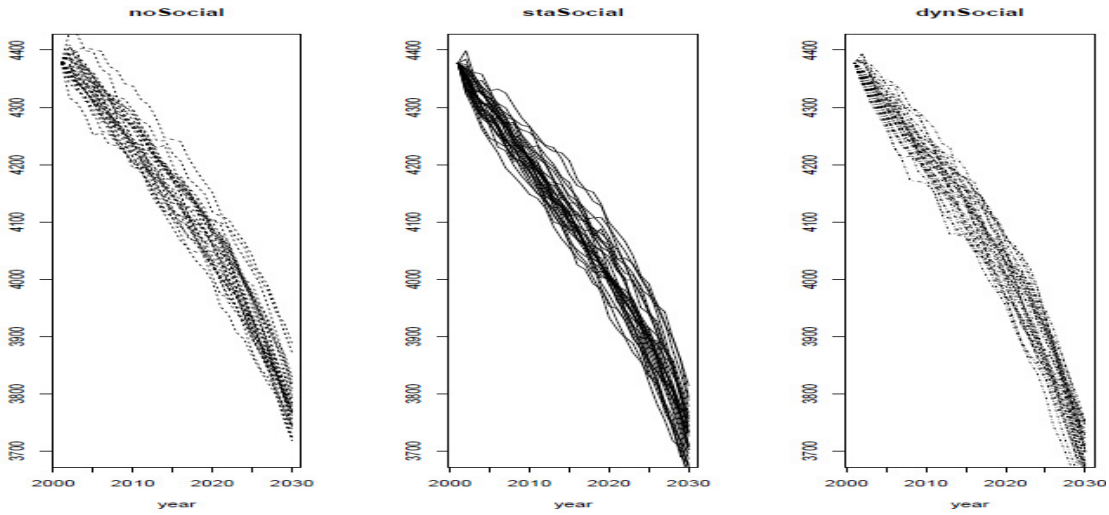
Buxton Central



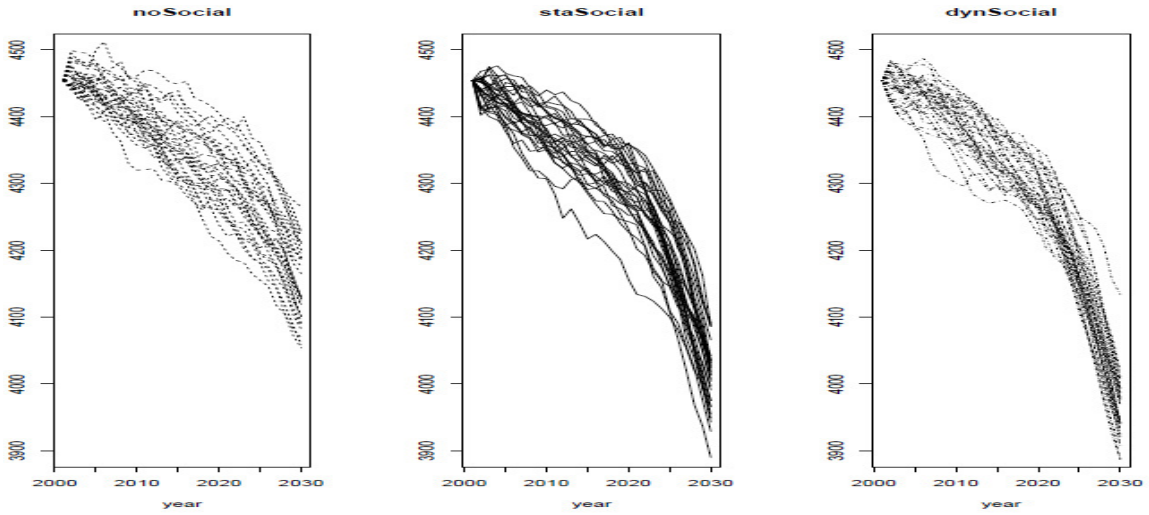
CoteHeath



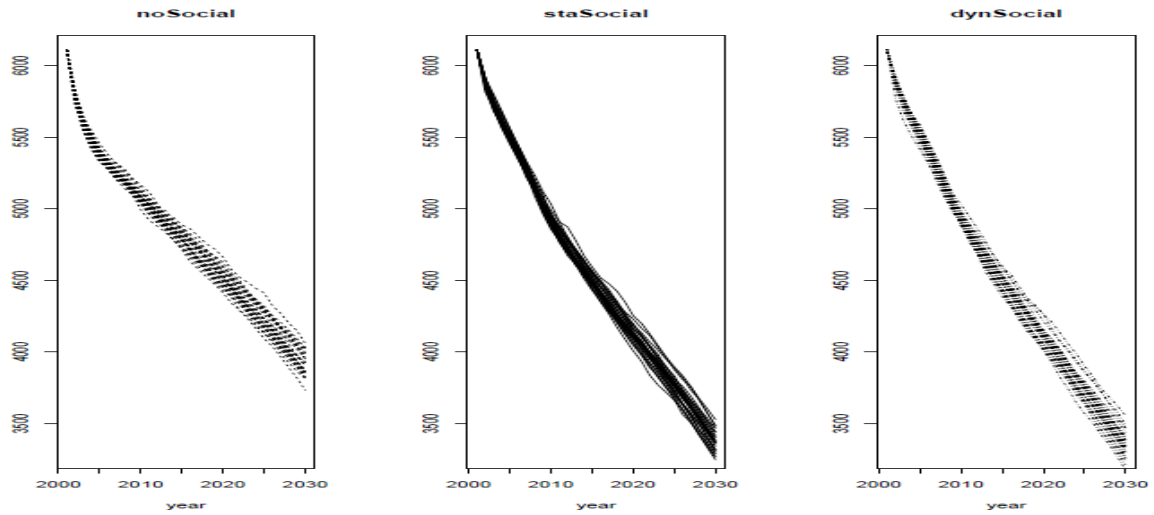
ChapelWest



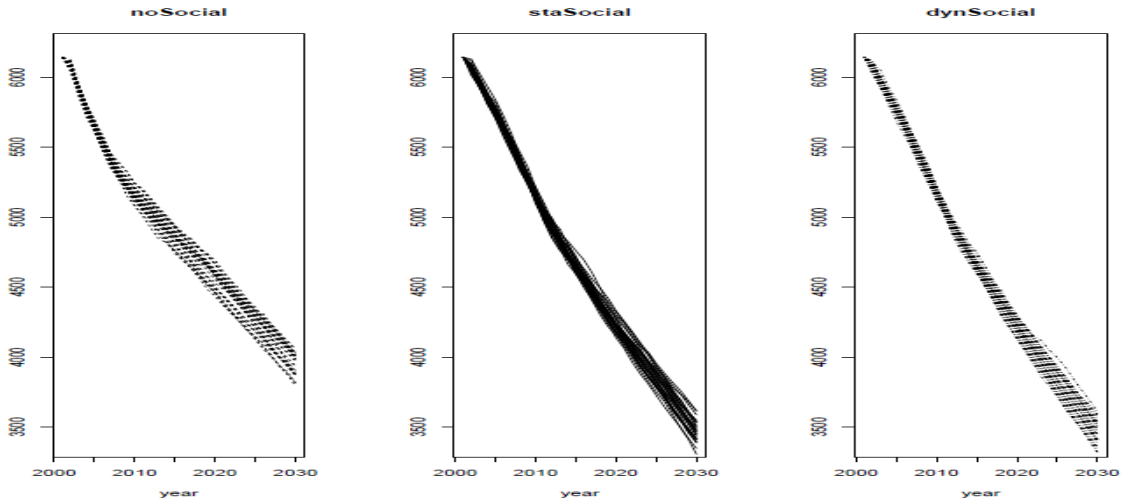
StoneBench



Brockwell



Dunston



St Leonards

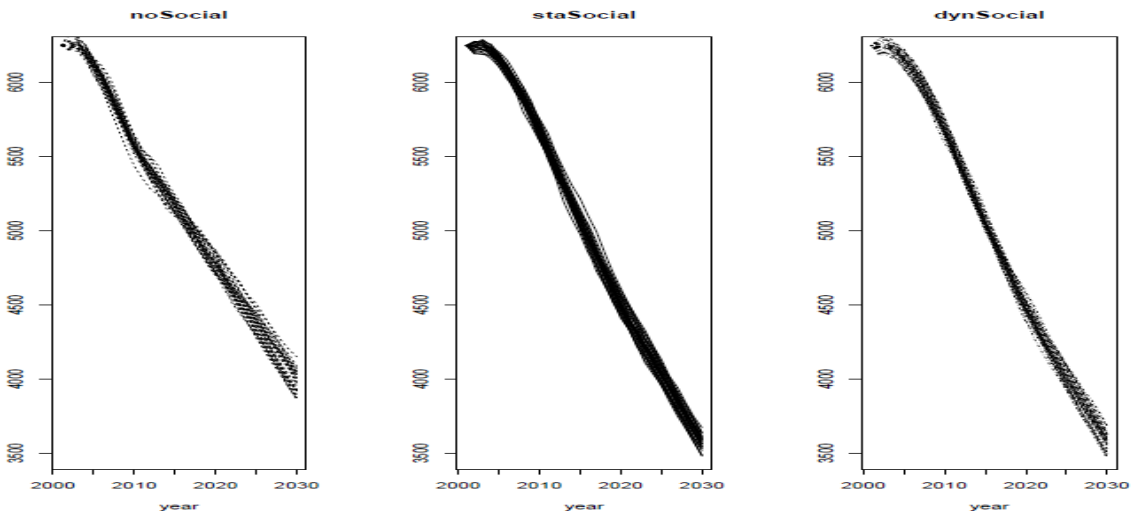
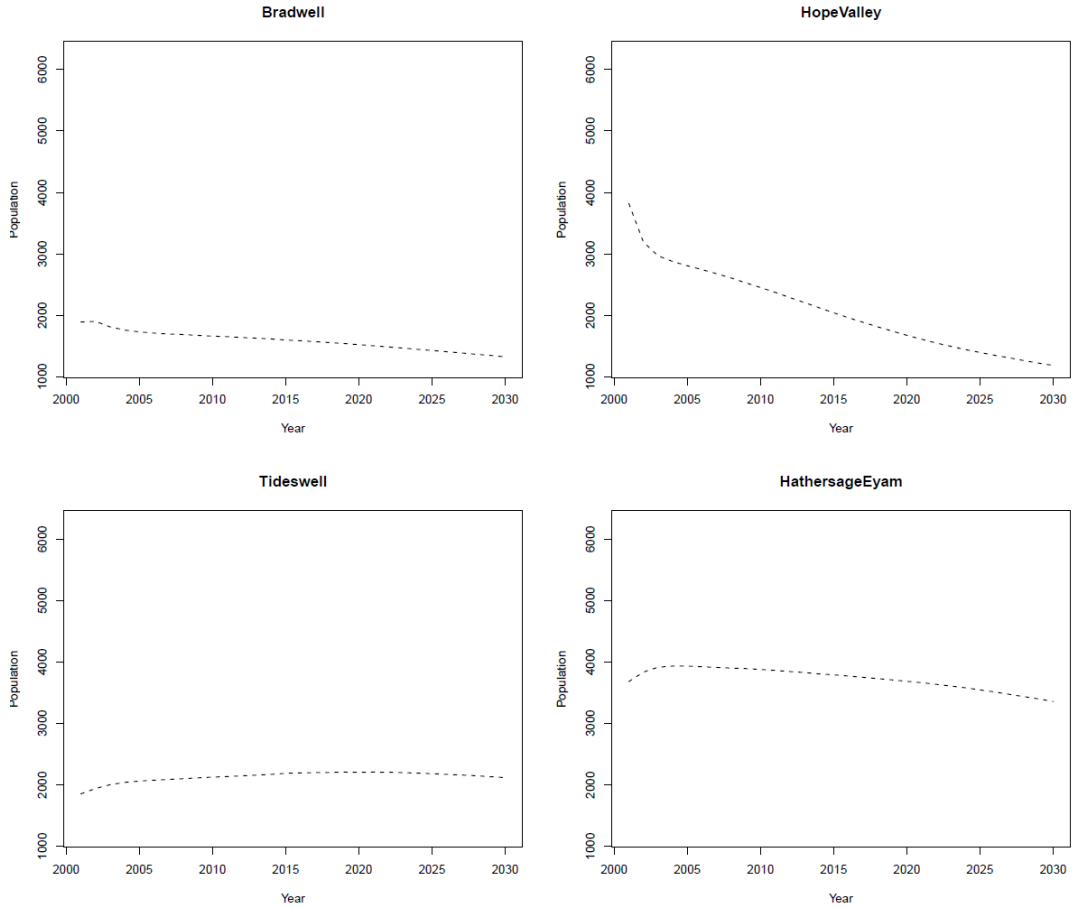


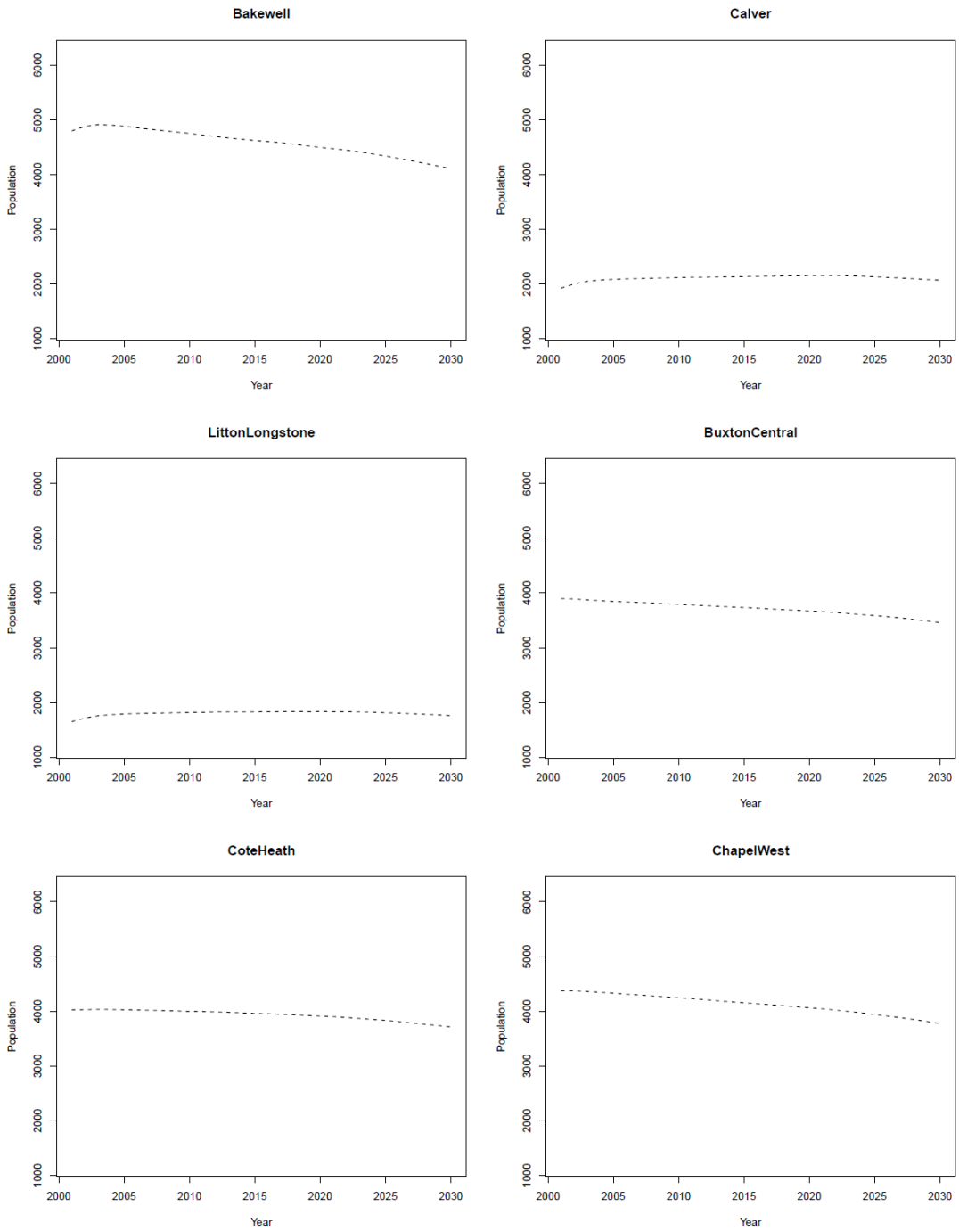
Figure 5. Ward-level population development in all simulation runs in noSocial, staSocial and dynSocial condition.

Looking at the population curves from different runs in one specific condition, we observe larger deviations in some wards (e.g. Tideswell, Calver) than the others. For most wards, we can say that the effects are robust. So next we will focus on analyzing the population development for the three conditions in the separate wards.

No social condition

In this section we will first focus on the no-social condition as a base condition to study population dynamics. In the following Figure 6 we show for each ward the average of 30 simulation runs in noSocial condition, simulating from year 2001 to 2030.




Bakewell
Calver
LittonLongstone
BuxtonCentral
CoteHeath
ChapelWest
Population
Year
1000
2000
3000
4000
5000
6000
2000
2005
2010
2015
2020
2025
2030

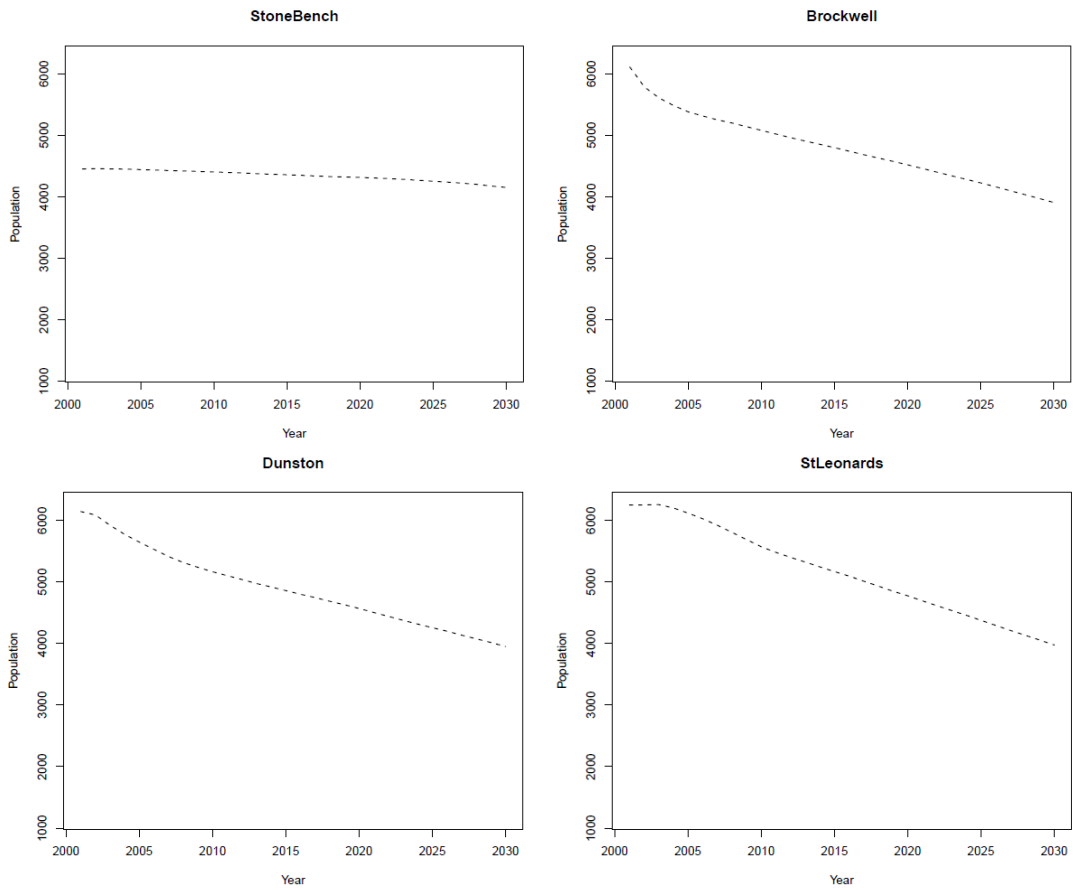


Figure 6. Averaged population development (in 30 runs) for each ward in noSocial condition

In Figure 6 three types of population trajectories can be seen:

(1) Significant decrease. Representative wards are: Bradwell, Hope Valley, Brockwell, Dunston, and St Leonards. For Bradwell, although the absolute number of decreasing population is not as large as others wards in this category, it has lost about 50% of population.

(2) Decrease. HathersageEyam, Buxton Central, CoteHeath, ChapelWest, Bakewell and StoneBench.

(3) Small increase. Tideswell, Calver, LittonLongston,

In Figure 7, wards are depicted with different colors according to the types of population trajectory developed in noSocial condition. The results demonstrate clear spatial patterns. Those wards of closer distance to outside regions are more likely to experience population decrease than the wards in the middle.

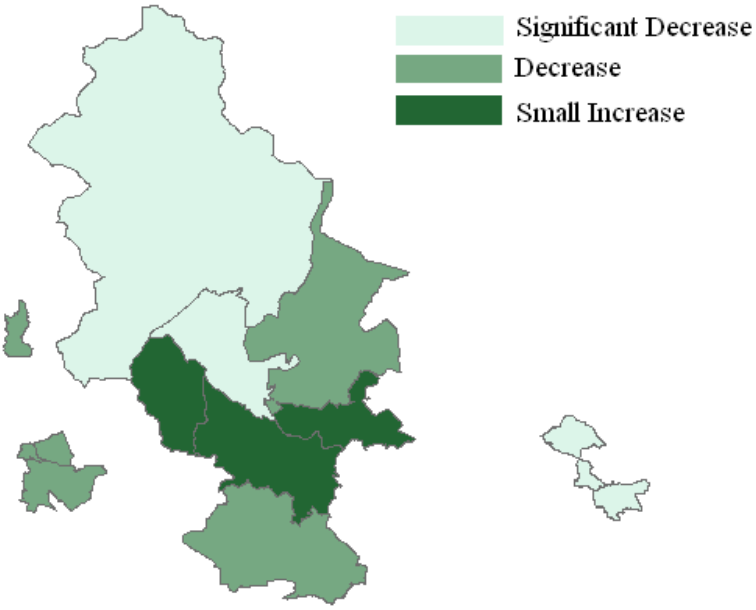
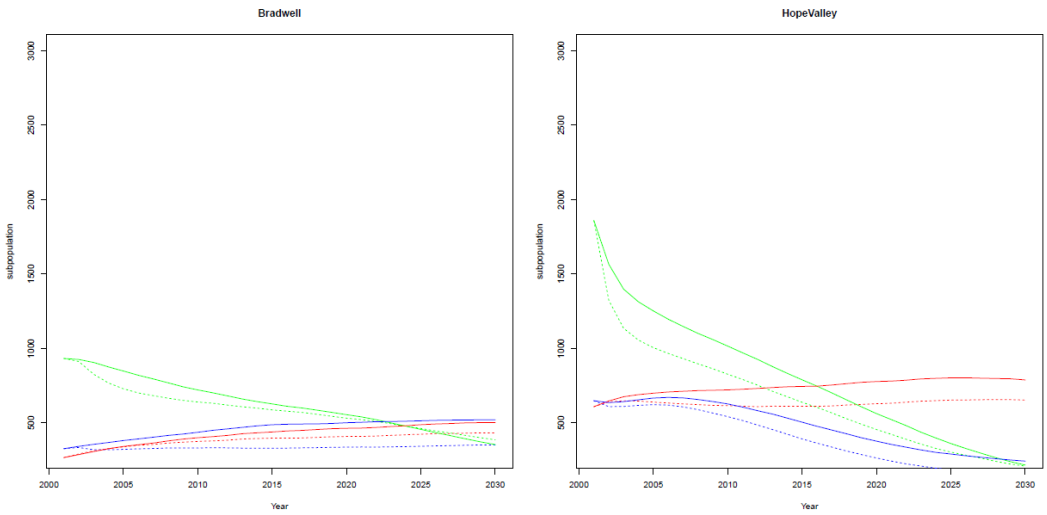


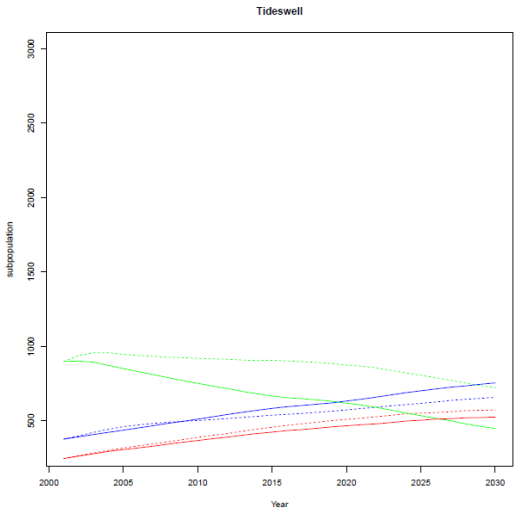
Figure 7. Different types of population change shown on map

On the aggregated ward level, it is not clear who is staying or leaving, so we need to know how this population change relates to different categories of inhabitants. The question is whether subgroups of population change differently. We continue to zoom in to analyze the dynamics in population structure. Such information is critical for micro-scale policy making. In Figure 8, we show the population dynamics for workers (in green), retirees (in red) and students (in blue).

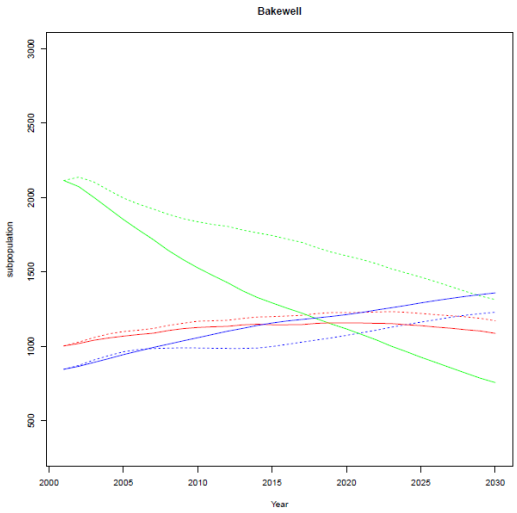
Bradwell HopeValley



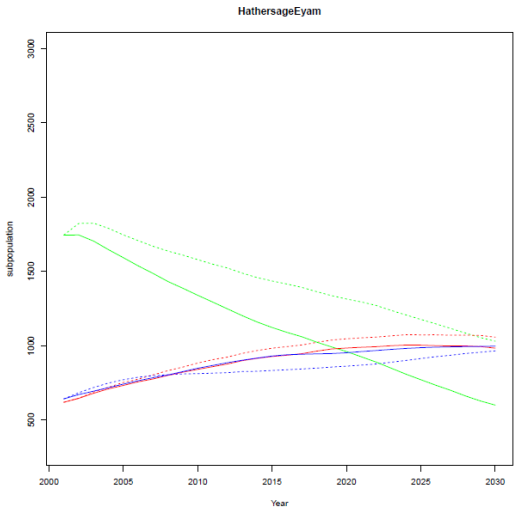
Tideswell



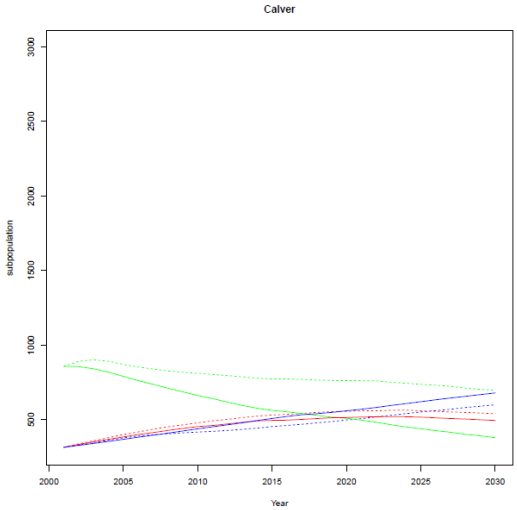
HathersageEyam



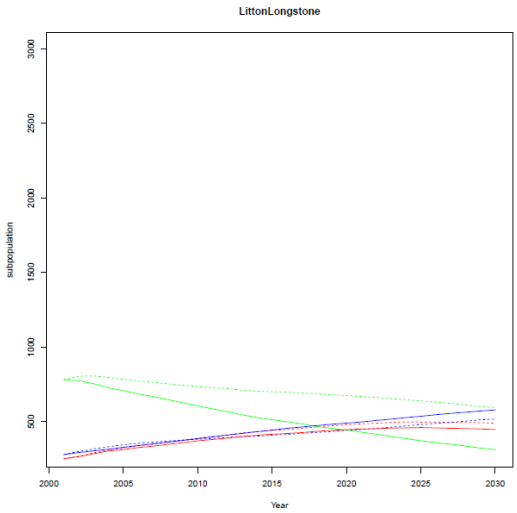
Bakewell



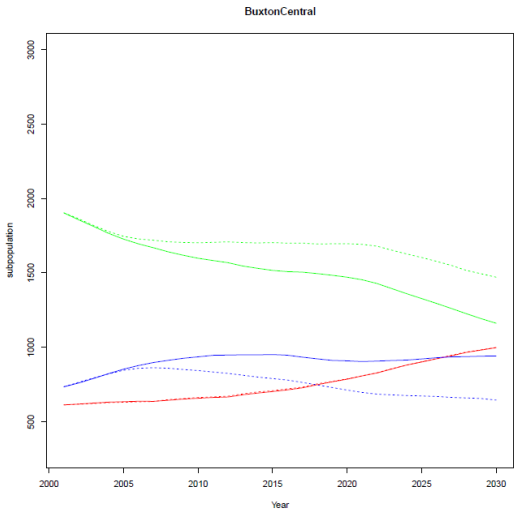
Calver



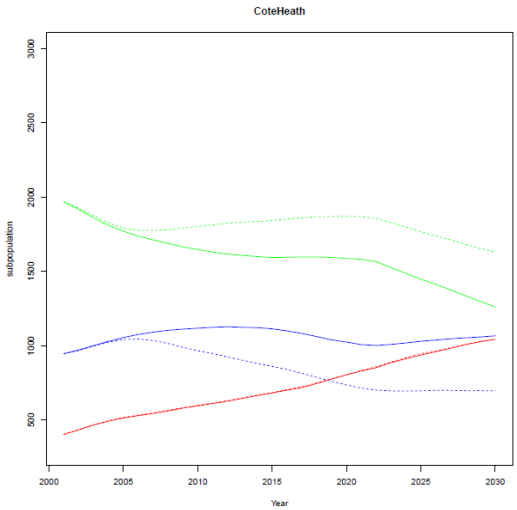
BruxtonCentral



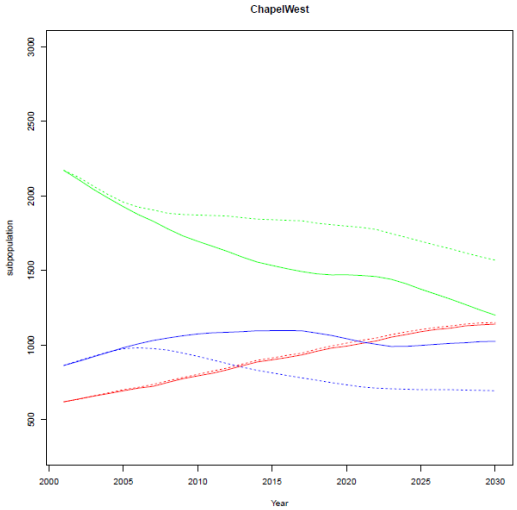
LittonLongstone



CoteHeath



ChapelWest



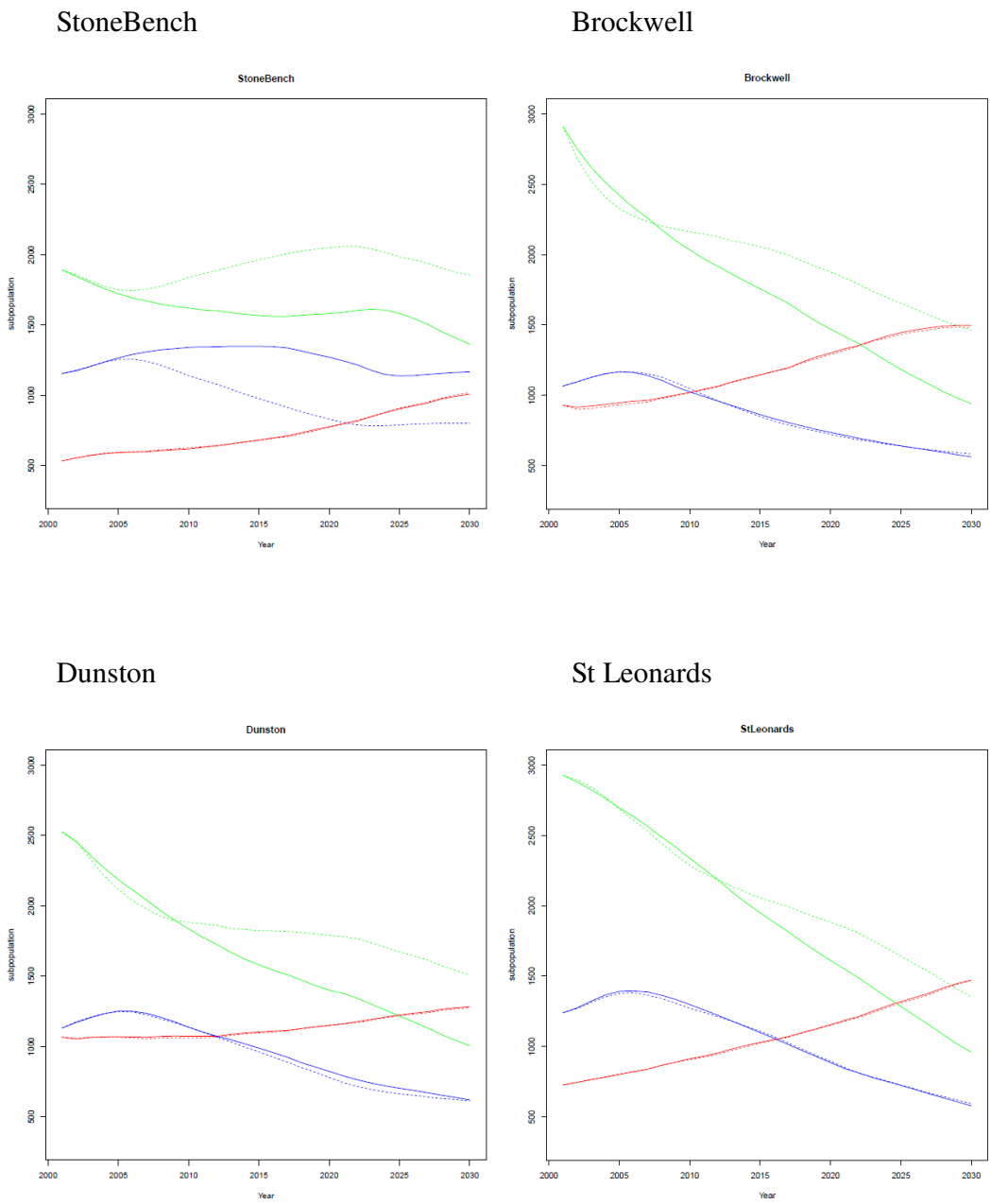


Figure 8. Averaged population of specific groups at ward-level in noSocial condition

Looking at two representative wards, Brockwell (4th row, 3rd column) and Tideswell (1th row, 3rd column), we observe for both wards that the workers' population appears to decrease the most; the number of retiree increases; but the trends of student population differ between the two wards. Such detailed information is captured only if we observe the simulated subgroups of population. To literally read the graph, Tideswell is more

attractive than Brockwell, particularly to retirees and students. We speculate that it is because of the higher service environmental quality in Tideswell (27.38) than Brockwell (13.685). For example, factors such as service quality, household structure, industry, locations and so on may all contribute to the attractiveness of a ward to specific group of population. We do not focus on this discussion here. Instead, based on our primary simulation results, we suggest local policy could take into account the interests of particular subpopulations to counter an outflow of inhabitants

The effect of social needs on population dynamics

In our model, social need is a concept stating that an agent prefers living close to his social contacts. An agent's satisfaction on social need is formalized as the proportion of an agent's social contacts that live within an agent's preferable maximum commuting distance. Our hypothesis is: social need has a twofold effect on population dynamics. When the social satisfaction is reasonable high, it may cause agents to stay despite lower economic and environmental outcomes. Under such conditions the social need will have a stabilizing effect on the population. If however the social need is dissatisfied due to the lack of social contacts, this will cause a motivation to leave. Agents that are moderately satisfied may decide to leave due to a drop in social satisfaction, and hence the social satisfaction may destabilize a population.

In a depopulating ward, the twofold effect of social need becomes visible. The presence of social needs will initially decrease the outflux of people for a certain period of time, and thus stabilize the population to a certain extent due to a positive social feedback. But if the population nevertheless continues to decrease, the social need becomes increasingly dissatisfied, and will motivate people to move as well. As this causes more people to become socially dissatisfied, we have a negative social feedback in the system causing the population to decrease faster than in a no social need condition.

Following this thought, we compare the difference in population development between the staSocial- and noSocial- condition. This can be made visually very clear by subtracting the average of 30 runs in noSocial-condition from the average of 30 runs in social-condition. The resulting graph shows the pure difference in population change for adding this social need. In Figure 9 we show this difference for all the wards.

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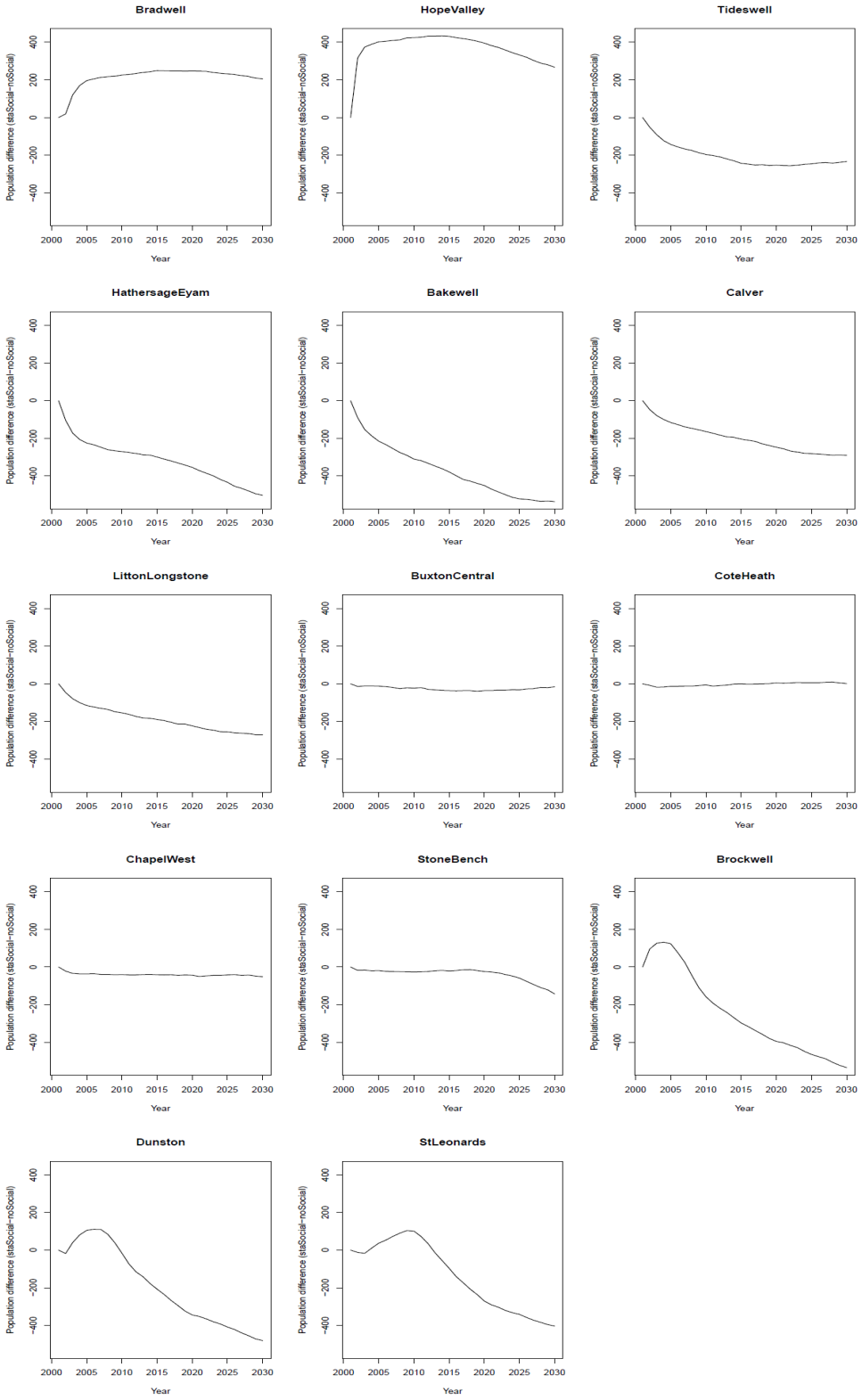


Figure 9. Difference in simulated population between noSocial and staSocial condition

The developments in the different wards are different, and we make a distinction between four types of effects of the social need, as depicted in table 3.

Table 3. Category of wards according to the captured effect of social needs

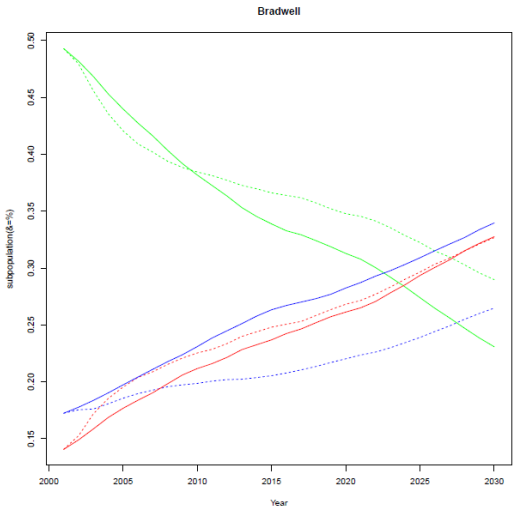
Type	Description	Wards
1	No effect	Buxton Central, CoteHeath, ChapelWest,
2	Long-stabilizing effect	Bradwell, HopeValley (possible explanation: the social cohesion in these two wards are high at the beginning. Agents' social needs prevent them from moving.)
3	Slow-destabilizing effect	Tideswell, Bakewell, Calver, HathersageEyam, LittonLongstone, StoneBench
4	Short-stabilizing, fast- and long-destabilizing effect	Brockwell, Dunston, St Leonards

Again, we focus on two representative wards: Tideswell and Brockwell. In Tideswell we see that the social need causes a progressive outflux of people. Here from the beginning only the negative social feedback is operating. If we compare this to the Brockwell ward, we observe that in the first years the population is larger in the social condition, thus indicating the presence of the positive social feedback. In 2009 this social feedback turns negative, as described above, and contributes to a faster population decline than in the noSocial condition.

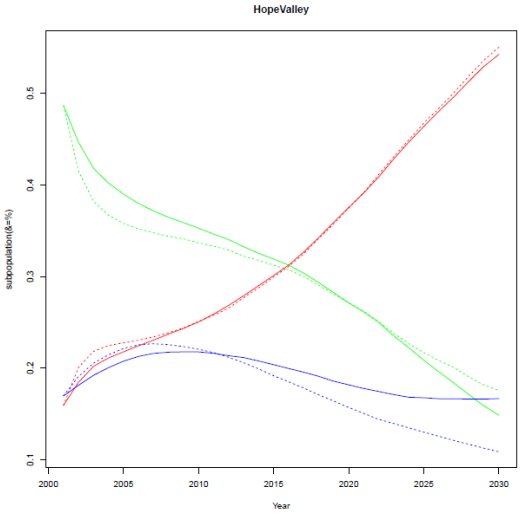
In the simulation of the 14 Wards, this transition from a positive towards a negative social feedback also was visible in Dunston and St Leonards. These three wards are with the largest initial population among the 14-ward-network. Through 30 years of simulation, they had the largest loss of population. It is essential to the concern of policy makers to identify this potential process and in particular to identify the individual wards with higher chances to experience this process. In another group of wards, we observe more significantly the first effect explained above. That is, social need plays a role in stabilizing decreasing population. (Bradwell and Hope Valley) In several other wards (Tideswell, Ha, Bakewell, Calver, LittleLonston), it seems that including social need speeds up the population loss

We have shown earlier that the subgroup of population develops differently in a ward. As a result, the population structure has changed over time. In Figure 10, we compare the percentage of each subgroup of population in a ward. Population of workers, students and retirees are respectively represented in green, blue and red. The solid line is from staSocial condition, and the dashed line is from noSocial condition.

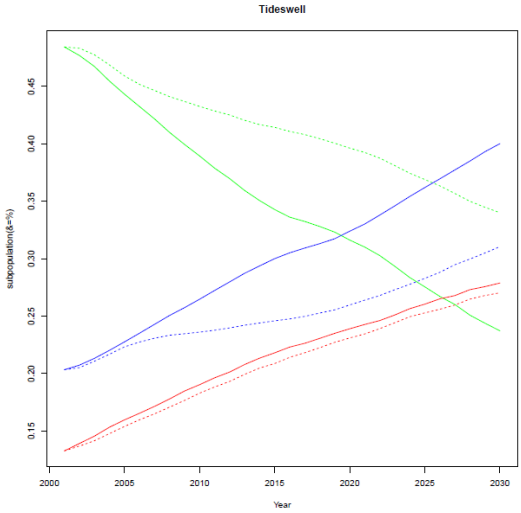
Bradwell



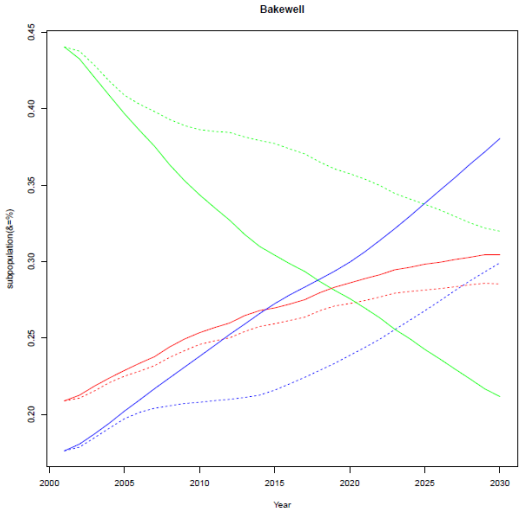
HopeValley



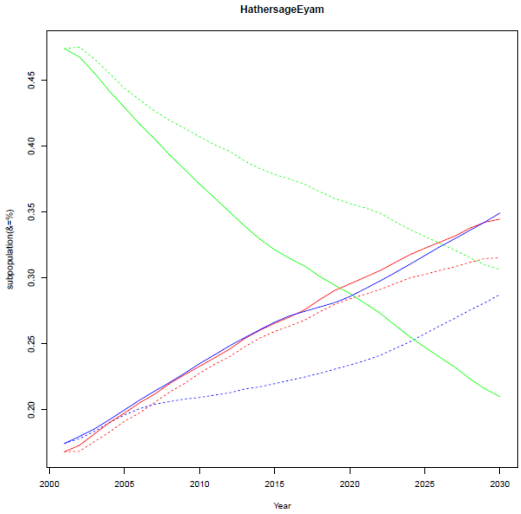
Tideswell



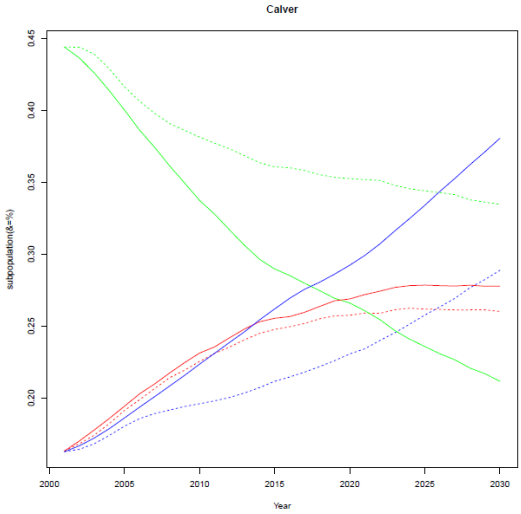
Bakewell



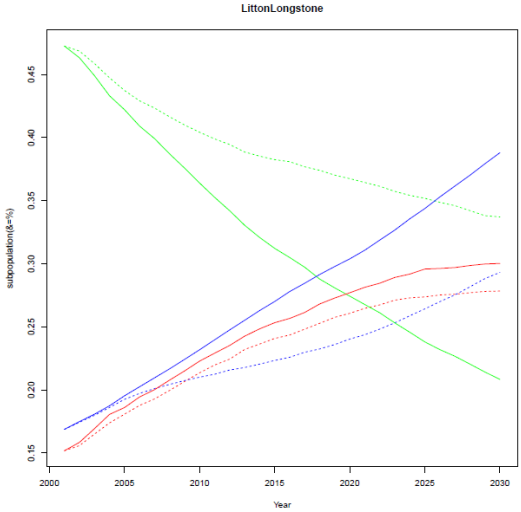
HathersageEyam



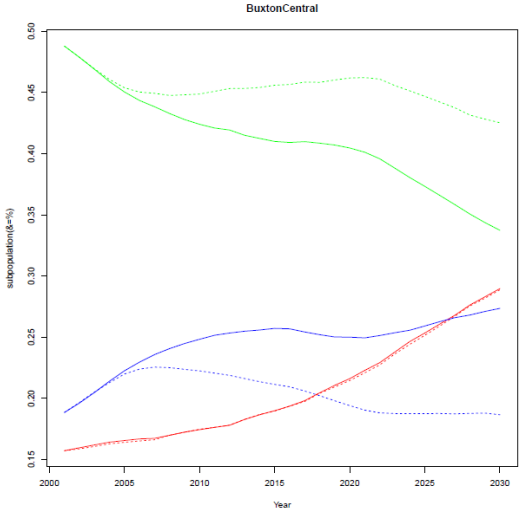
Calver



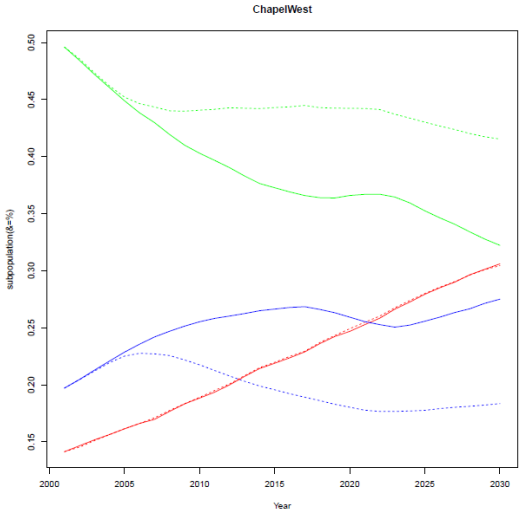
Littonlongstone



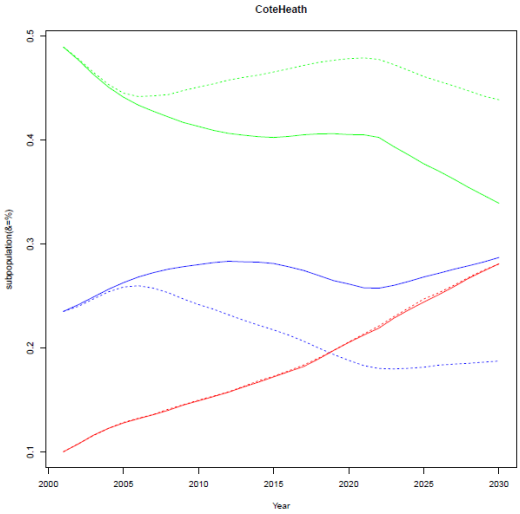
Buxton Central



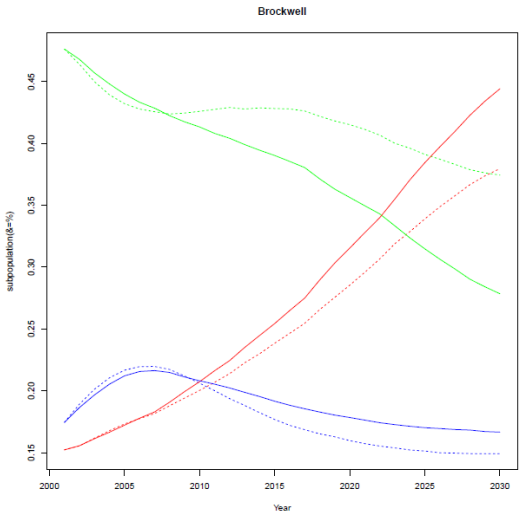
Chapelwest



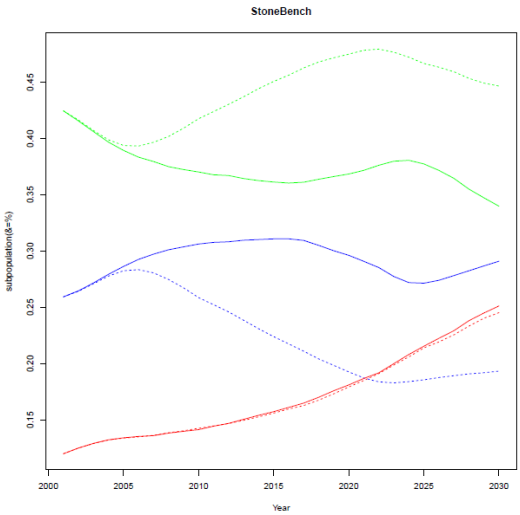
CoteHeath



Brockwell



StoneBench



Dunston St Leonards

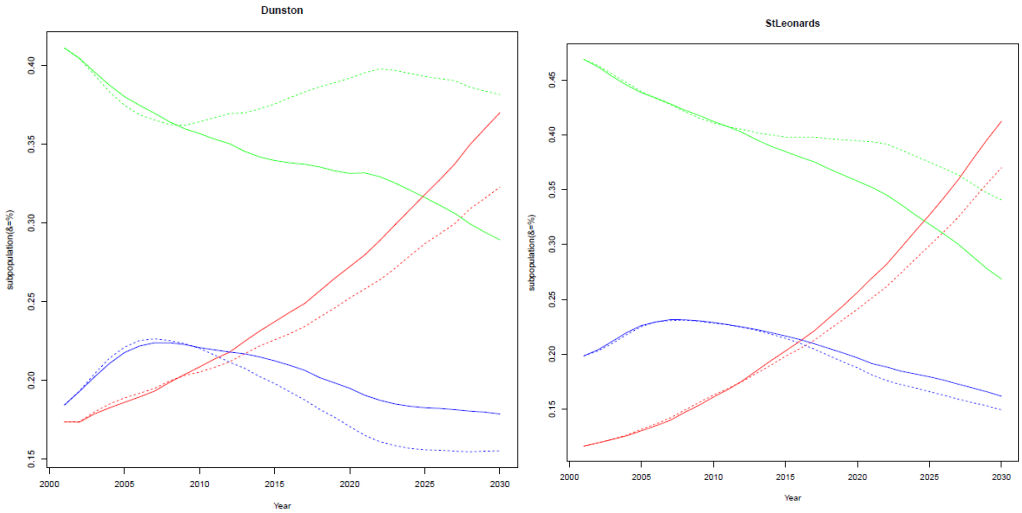
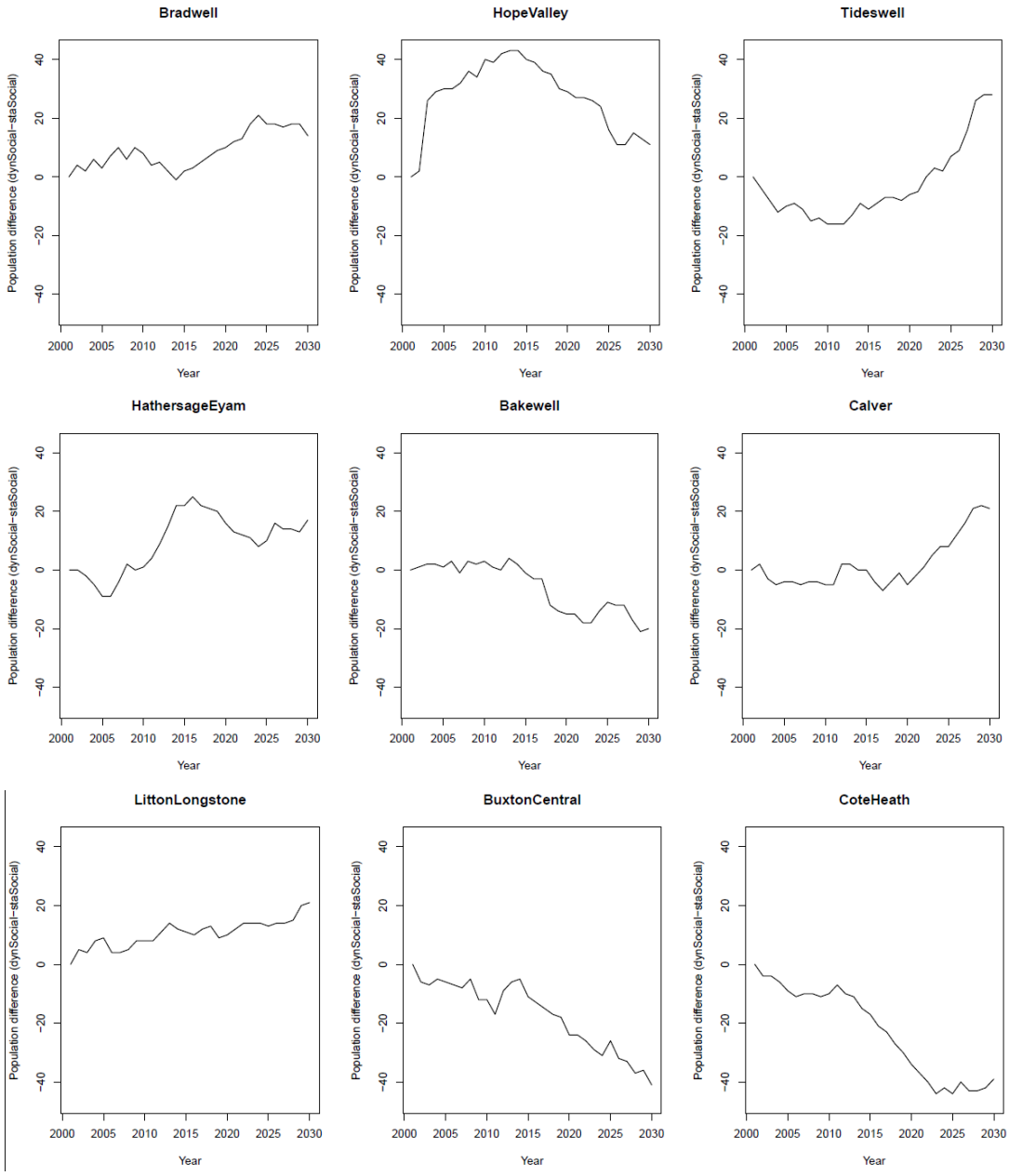


Figure 10. Ward-level difference in the average proportion of subpopulation (retiree, student and worker) between noSocial and staSocial condition.

Static versus Dynamic networks.

In real society, when people change to a new job or move to live at a new place, they get to know other people. An agent's decision becomes more influenced by these contacts as a result of more frequent interactions with them. Normally, people are only able to maintain a limited number of social contacts, due to cognitive constraints. The tie between one and his contact with whom he interacts less frequently gradually decays. For a better fit to this process, we have implemented a procedure for an agent to update his social contacts, and test in dynSocial condition. The sources of this update can be threefold. First, the individual agent itself changes job or residence place. Second, a contact of the agent changes status causing their interactions to decrease. Third, the agent becomes close contact with another agent which wasn't in his social network due to the other agent's change of status.

Including social need and dynamic network, the total population after 30 years is significantly different from the noSocial condition (ANOVA test between noSocial and dynSocial, $F=2055.347$, $df=1$, $p<.05$). However, there is no significant difference between staSocial and dynSocial (ANOVA test $F= 2.32$, $df=1$, $p=.13$). This indicates that our implementation of dynamic network does not have a significant effect on the total population change on the aggregated 14-ward network, comparing to condition when agents have a static social network. We further zoom in to compare the population development in each ward. Figure 11 shows the result for subtracting the population in staSocial-condition from the dynSocial-condition, thus presenting the pure difference between the two conditions.


Bradwell
HopeValley
Tideswell
HathersageEyam
Bakewell
Calver
LittonLongstone
BuxtonCentral
CoteHeath
Population difference (dynSocial−staSocial)
Year
40
20
0
−20
−40
2000
2005
2010
2015
2020
2025
2030

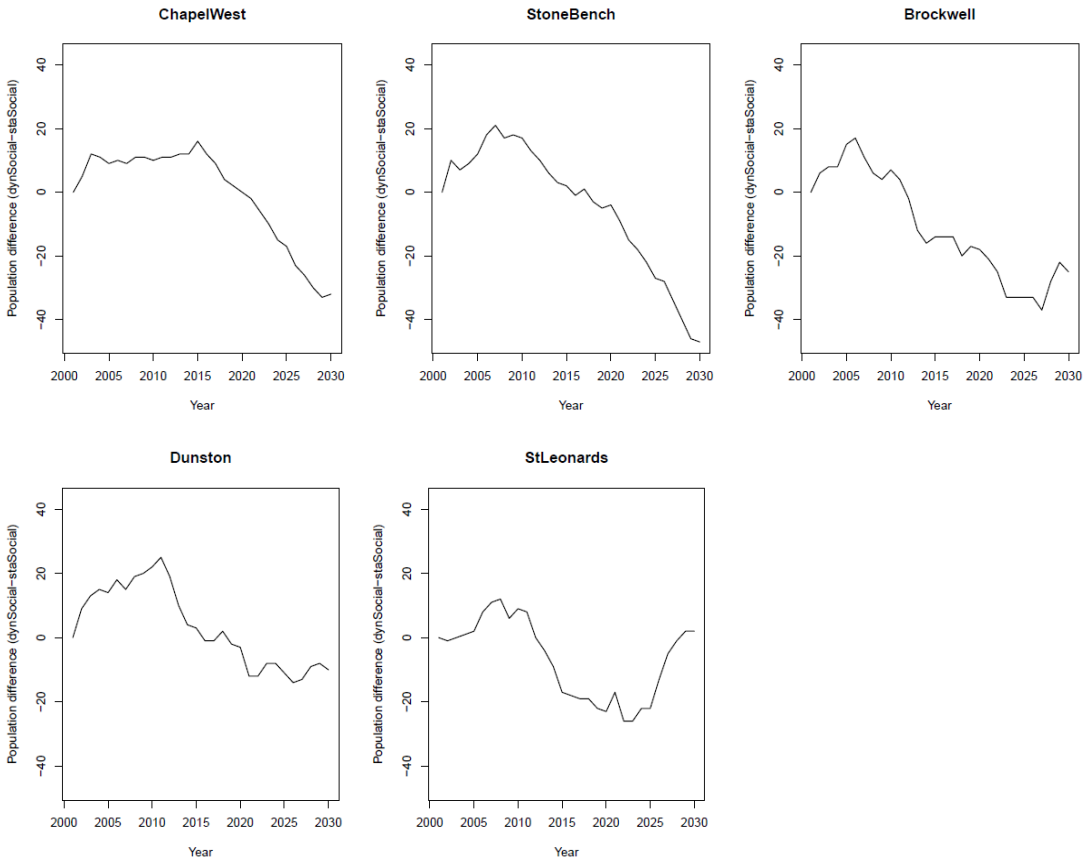


Figure 11. Difference between staSocial and dynSocial condition Brockwell Tideswell

We can see the maximum difference within 14 wards is less than about 40 people. We have also compared between two conditions the development of subpopulation. The results (two examples given in Figure 12) show that subpopulation in two conditions develop very similar to each other.

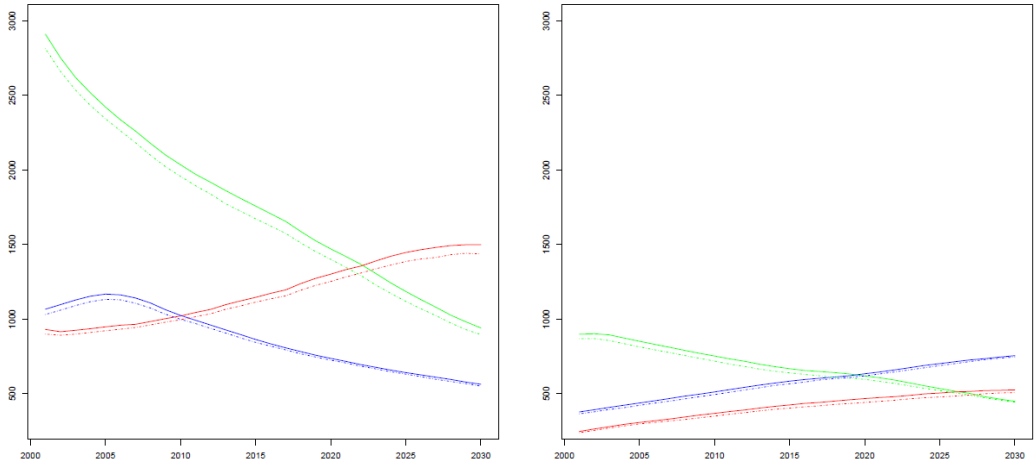


Figure 12. Subpopulation in staSocial and dynSocial condition (solid line: staSocial, dashed line: dynSocial)

We can conclude that within the effect of including a dynamical network between the agents has a negligible effect on the population dynamics. Concerning the extra computational demand it can be concluded that using a static network in successive simulation experiments seems justified.

5. Conclusion and discussion

The experiments we present in this report demonstrate that in particular social needs may have a strong impact on population dynamics. Most interestingly is that in the context of a declining population the presence of a social need causes the population to initially decrease at a slower rate, until a critical population size is reached, after which the population decrease accelerates. Hence initially the social need exerts a stabilizing effect, which is caused by the effect that despite the presence of economic more attractive areas elsewhere, the social satisfaction the agents derive from living in the vicinity of friends is a strong motive to stay. However, given that a lack of good jobs causes a decline in the population, the social satisfaction will decrease as a function of the number of friends that move. This causes that the social satisfaction that originally functions as a driver to stay transforms in a driver to move. And the more agents leave the ward, the lower the social satisfaction of the remaining inhabitants will be, which drives them to move as well. At this stage the decline in social satisfaction is a self-amplifying process, accelerating the moving of people. This is typically what happens in the ward of Brockwell, and we observed this in other wards dealing with a substantial population decline as well. This signifies that when a population is decreasing due to economic reasons, this decline can accelerate if a certain threshold has been passed. Also it can be expected that the stronger the social cohesion in a ward, the sharper the transition between the slow and fast population decrease stages will be.

That a ward having the reputation of providing good social capital displays a sudden fast decline may come as a surprise to policy makers. For the policy maker the question thus is how to anticipate such a sudden population decline and how to prevent it, if possible and desired. The empirically parameterized model we developed allows having a deeper look at the attributes of the agents that are moving away. This makes it possible to make more fine-grained projections of what type of people are more likely to move away, and for what reasons. Looking at the population dynamics for different categories of inhabitants of Brockwell (Figure 4b) one sees a strong decline in the workers, a smaller decline in the students, and an increase in the population of retirees. For the policy maker such simulated projections may support strategic decision making. For example, the policy maker first may try to develop a strategy to avoid existing workers and their children (students) leaving the ward. This would probably require the creation of jobs. The model allows for exploring how creating jobs in different socio professional categories and sectors of activity may match with the qualification of the agents that are prone to move. It would also be possible to explore if the qualifications of workers would match with an increased demand for services of the retirees that move to the ward. Retirees are attracted to the area, probably because of the environmental quality. If this is good for the vitality of the ward, policy makers may consider possibilities to stimulate this. Ideally this may result in a strategy to create jobs around servicing retired people,

thus making the ward more attractive for all groups. Hence one can imagine that investments in particular activities and services in which retirees are interested would benefit the population at large. Obviously the precise strategies cannot be derived from the simulation model, but this downscaling of population dynamics using an agent based model illustrates the possibilities of identifying the possible developments in the system at a detailed level, which in turn is helping to focus the policy making effort at potential effective policies at the specific ward level. This level also fits well with the scale of EU community funding policies aimed at supporting the viability of mainly depopulating agricultural areas in Europe. Having a simulation tool that is capable of exploring the population dynamics at the same level as the policies that are implemented opens a perspective on developing more effective policies, and possibly on testing policies using the same simulation tool.

Concerning the modeling of the networks of agents, we tested the difference between static and dynamical networks. The experiments with the dynamical network did not result in results that deviated strongly from the static networks. Whereas statistical testing indicated significant differences, in most cases the relevance of the difference was rather limited, in particular when considering the large impact the social need had. The question thus is if it is necessary to include such dynamical networks, in particular considering the significant computational effort that is associated with it. We conclude that unless there are clear arguments for using such a dynamical network, for most regional population models such dynamical networks are not necessary to include in models.

Further applications of the model

The project produced an agent based model that can be used to simulate population dynamics using a relative simple model of human behaviour, allowing for the simulation of large numbers of people. This opens the possibility of simulating developments in the population for different categories of people, allowing to explore population dynamics at a very detailed level, e.g. for age categories, occupation, educational level and so on. For applying this model to a certain region it is required that sufficient data on the population are available. Concerning data on economical conditions usually a lot of detailed information is available. On most areas statistics are available on the demographic composition of the population concerning age, education, household situation, jobs and income. Concerning the social satisfaction usually less or no data are available. Depending on the available budget it is possible to conduct a large survey among the population to measure their social satisfaction, or to leave this to experts that rate the social satisfaction of e.g. certain neighbourhoods, using proxies such as the number of local activities (hobby clubs, sports, presence of a school etc.). Also a challenge is the parameterisation of the environmental need. In the current study we used the housing price as a proxy for environmental quality, as this is capable to capture rather different environmental preferences of people, but we are aware that more elaborate ways exists to measure environmental quality. However, the essence is that the populations experience

of environmental quality and satisfaction is being measured, so for the time being relative simple proxies may be sufficient.

For a more accurate empirical implementation of the model, it is desirable to collect the following data:

- Job openings every year in each sector and each social professional category.
- Residence openings every year in each ward.
- Information on population moving to live in the modeling region from outside.
- Personal threshold values to specify individual's social need, economic need and environment need;
- Personal preference weights to specify individual's preference on different need;
- Information on the social network of the modeling population, to testify the construction of individual's network and its updates.

Given sufficient data are available the model can be applied to study the population dynamics of municipalities in a detailed level. A next step would be to experiment with policy measures. For example, in the model we could test how the creation of particular types of jobs, or the development of environmental quality and possibly associated tourist business might have an impact on the viability of a community. Moreover it would be possible to get insights on how such policies were implemented in a wider geographical area. This allows testing different scenarios of for example using the same policies in all the communities in an area, or focusing on different developments in different communities. The simulation model might give indications if a homogeneous or heterogeneous development is preferred for a region as a whole.

Concluding we can remark that such an approach allows for many experiments and the communication with stakeholders becomes more difficult if they are confronted with an overflow of experimental results. For communicative purposes we expect that a gaming context is effective in communicating how policy might interfere with the population dynamics (e.g., Jager, 2010). Gaming offers a method where stakeholders can interact with a simulation model, and may provide a viable method of studying the management of social complex systems, also using experimental methods. This is expected to provide a tool for future explorations of how the viability of communities can be stimulated by developing policies addressing specific groups of (potential) inhabitants. In that sense we hope that the model we have developed will contribute to the development of efficient EU policies for local communities.

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Appendix: List of State Variables

The model comprises of three levels of entities: individual, household, and ward.

An individual is characterized by the state variables as listed in Table A.

A household consists of a number of individuals who have family relationship and live together. Table B lists the state variables of a household.

A ward is the environment that a household and individuals live or work in. There are three types of wards in terms of their locations: ward-in-net (including 14 wards within the focusing area of study), ward-in-region, and ward-out-region. The state variables of a ward are listed in Table C.

Table A. State variables of individual

Variable	**Explanation**
Household_ID	Identity of the household which an individual belongs to.
ID	Identity of the individual within its household.
Age	Individual's age.
ResWard	The ward where the individual lives in.
WorkWard	The ward where an individual works in.
WorkStatus	An individual's working status. Possible values are student, worker, unemployed, retired and inactive.
Social Professional Category	An individual's socio-professional category, if it is worker or unemployed. Possible values are the following 6 levels. Level 0: Managers, senior officers, and professional occupations. Level 1: Associated professional & technical occupations. Level 2: Administrative & secretarial, and skilled trades occupation. Level 3: Personal service, and sales & customer service. Level 4: Process plant & machine operative. Level 5: Elementary.
Sector of Activity	An individual's sector of activity. Possible values are: 0: Agriculture, hunting, forestry 1: mining, quarry, energy supply 2: manufacture 3: construction 4: wholesale, retail, repair 5: hotel, restaurants 6: transport communication 7: financial, real estate, renting, business 8: public sectors

	9: others	
Income	The monthly income of an individual.	
Qualification	An individual's education/qualification level. Possible values are: 0: no qualification 1: NVQ1 2: NVQ2 3: NVQ3 4: NVQ4 5: NVQ5 6: other qualifications	
Satisfaction weights	Wsoc	social
	Weco	economic
	Wenv	environment
Threshold values in satisfaction	$Pro_{min}(a)$, $Pro_{max}(a)$	social relation threshold
	$Env_{min}(a)$, $Env_{ideal}(a)$, $Env_{max}(a)$	Environmental threshold
	$Income_{min}(a)$, $Income_{max}(a)$	income level threshold

Table B. State variables of a household.

Variable	Explanation
ID	Identity of the household within its residence ward.
ResWard	The ward where the household lives.
Type	A household type, with the following possible values: 0: single 1: mono-parental family. 2: couple without children. 3: couple with children. 4: others.
Members	The list of individuals belong to this household.

Table C. State variables of a ward.

Variable	Explanation
Type	Type of a ward in terms of where it's located. InNet: the ward is one of the selected wards within a ward network. InRegion: the ward is outside the selected ward network, but inside the studying region. OutRegion: the ward is reachable outside of the studying region.
Households	The list of households that are living in the ward.
workAgents	The list of individuals who are working in the ward.
JobVacancy	The list of available jobs. Each job is specified with its sector, required social-professional category or qualification.
commuteDis	Commuting distance between this ward and another ward.