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The Dynamic Spatial Simulation Modelling of the Effects of Land Use Change on Avian Species

Burak Güneralp
University of Illinois at Urbana-Champaign
Department of Natural Resources and Environmental Sciences
S. Goodwin Ave. Urbana IL 61801 USA
Telephone:++1 217 333 93 49
Fax:++1 (217) 244-3219
guneralp@uiuc.edu

Abstract

A spatial dynamic simulation model for two bird species was constructed. It is developed as a part of a greater project being carried out in University of Illinois at Urbana-Champaign. The project LEAM is about analysing urban sprawl in the United States and developing policies to prevent it. Under LEAM project, a comprehensive urban development model of Kane County in the state of Illinois was constructed. The model presented in this paper is an integral part of the LEAM model and serves as a means to evaluate the effects of urban sprawl on two bird species selected as indicators for their ecosystems: Eastern meadowlark (*Sturnella magna*) for the grassland, and ovenbird (*Seiurus aurocapillus*) for forest ecosystems. The model is capable of running for both species with the help of a 'switch' variable. The model was integrated with a hypothetical land use map through a spatial analysis software, Spatial Modelling Environment (SME) and tested for behavioural validity. Non-spatial results were used for verification and calibration; spatial results revealed the extent of effects of urban sprawl on avian species in particular and wildlife in general. Lack of sufficient data was a significant problem during the study and it is believed that the model could be improved with the availability of more data on population dynamics and habitat requirements of grassland and forest bird species. The spatial modelling studies are still novel approaches and their success partly depends on availability of relevant and sufficient data. There is still much to improve in this field and it is realistic to expect great contributions to the scientific and practical theory from spatial dynamic modelling in the future.

Keywords: Urban sprawl, land use, habitat loss, habitat degradation, avian species, system dynamics, spatial modelling.

I. Background

Ecological models need to represent spatial characteristics of species' habitat adequately to be accurate representations of the reality. Until recently, ecological models have been constructed without explicit consideration of the spatial nature of the problem at hand. This requires assuming that the habitat modelled is more or less homogeneous which is not the case most often in real life. Habitats are often heterogeneous and there are spatial interactions going on between various elements of the system. Moreover not only the area sum but also the spatial arrangement of habitats plays a vital role on the population dynamics of species. With the advance of computer technology and geographic information systems, it is possible to construct spatially explicit models. This gave way to come up with ecological models capable of simulating both on spatio-temporal domain. What this means for land use managers and decision makers is more realistic models that can be used more effectively by them.

Land-use changes in the United States lead to enormous uncontrolled habitat alterations that influence plants and animals (Turner *et al.*). Poorly planned urban development also causes unnecessarily high infrastructure costs to the society that could otherwise be avoided. This paper deals with the analysis of urban sprawl effects on wildlife bird species. It is part of a greater research project being carried out in University of Illinois at Urbana Champaign. The research project is also supported by the CERL and aims to evaluate and analyse urban sprawl in United States. The study area of the research project is Kane County near the Greater Chicago Area in the State of Illinois. Urban development patterns in Kane County are studied to uncover its causes and to determine its probable effects on wildlife, economy, and social structure of the county through dynamic simulation modeling. Potential policy options to prevent the adverse effects of urban development can be developed using the LEAM model platform.

The bird model presented in this paper was integrated with the LEAM model platform. The platform, apart from the bird model, consists of models developed for other indicator species such as raccoons and frogs, and models related to hydrological and socio-economic dynamics of the county. An interactive version of the large-scale regional model with its social, economic, and ecological components can be reached from the website http://www.rehearsal.uiuc.edu/leam/. The regional model serves as an experimental simulation platform where different aspects of urban sprawl can be analysed from a holistic point of view where the social, economic, and ecological

esented in this paper, a hypothetical dynamic landscape was used. The hypothetical land use map has a number of land uses ranging from grassland to high intensity residential in accordance with the national land cover data (NLCD) definitions (http://landcover.usgs.gov/classes.html). The resulting model has a fairly generic structure and it is possible to employ for other species by only changing the relevant parameters with no or little structural modification.

II. Selection of Indicator Species

An indicator bird species for grasslands was used in the model since grasslands are the characteristic wildlife habitat in and around Kane County. An indicator bird species for forests was modelled also to be used in another project for a mostly forested region in the State of Georgia. The model runs for only one species at a time. The indicator species to be simulated is selected with the help of a boolean variable in the model.

The indicator species for grasslands is Eastern Meadowlark (*Sturnella magna*). It is a typical grassland bird species. It is used in the Kane County urban sprawl project. The indicator species for forests is Ovenbird (*Seiurus aurocapillus*). It is already a threatened species and therefore serves as a good ‘conservative’ indicator species. According to Simons *et al.* (1999), the species is listed as one of the High Priority Southern Appalachian Bird Species. It will be used in another urban sprawl project in the State of Georgia. There is considerable amount of information on both species in the literature.

Conducting research on birds has its own challenges. First, due to the length of observation time required and difficulties in observing large areas, research on birds generally provide little information on their lifecycles. Moreover, studies on the same species but from different locations may produce irrelevant even conflicting results. Finally, there is little information on factors affecting neo-tropical birds in wintering grounds and during migration periods and how they respond to them. The approach here was to use information sources from studies conducted at locations close to the project sites.

II.I. Eastern Meadowlark (*Sturnella magna*)

The range of Eastern Meadowlark is widespread in the eastern United States and southeastern Canada extending as far west as Arizona. It is also resident in the Bahamas and extends south to Mexico (Figure 1). These birds are chunky, ground-dwelling birds and can be found in grasslands, pastures and prairies, but the population has been reduced due to urban areas, and reservoirs.

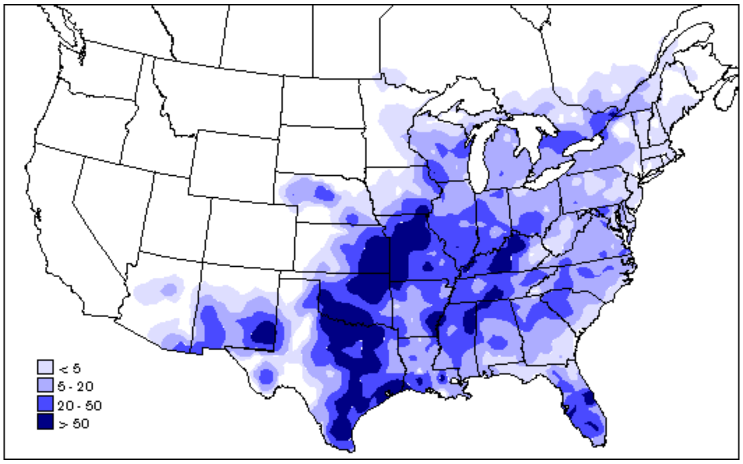

Figure 1. Breeding distribution of the Eastern Meadowlark in the United States and southern Canada, based on Breeding Bird Survey data, 1985-1991. Scale represents average number of individuals detected per route per year. (Price et al.. 1995).

In spring, the male arrives first to the nesting grounds and establishes his territory. The females arrive approximately 7-14 days after. The male's success depends on the territory and his song. Males are polygamous and defend their territory, which is large enough for two or three mates. Nesting begins late March to early May. The nest is built on the ground in meadows, cornfields or weedy orchards. Throughout the months of April to August, 4-5 eggs are laid. The female incubates the eggs which takes anywhere from 13-14 days and broods the young. The first young will leave the nest within 11-12 days. Nest on ground concealed by tall grasses (Bird Nature, 2001).

This bird's diet consists of about 70-75 percent insects such as grasshoppers, crickets, beetles, ants, spiders, and wasps. In winter, they eat grains and weed seeds.

II.II. Ovenbird (*Seiurus aurocapillus*)

Ovenbird is a neotropical bird species. It is a very vulnerable forest dwelling species is a good indicator on the health of forests in Georgia in particular and within its habitat range in general.

The range of this forest-interior dwelling bird extends from central and eastern Canada to northeastern and north central United States (Figure 2). Its breeding habitat is large mature deciduous forests and pine. The species nests are located in the open on the ground. Adult females leave 4-5 eggs per nest. Incubation lasts 11 to 13 days fledging 8 to 10 days.

Ovenbirds may be more successful raising young in larger forests than in isolated forest fragments. Donovan *et al.* (1995) suggested that long-term viability of Ovenbird populations, as well as those of wood thrushes (***Hylocichla mustelina***) and red-eyed vireos (***Vireo olivaceus***), depend on the maintenance of heavily-forested landscapes throughout the breeding range (Conservation Commission of Missouri Report).

The ovenbird belongs to the warbler family of songbirds. It stays mainly on the forest floor where it forages and builds its nest. Ovenbirds winter in Mexico, Central America and northern parts of South America. Besides flying thousands of kilometres, these birds must face habitat loss on two fronts. Large portions of the rainforest in South and Central America are being cleared and burned to make room for mines, settlements and ranches. They return to Saskatchewan around the middle of May. Scientists call these birds neo-tropical migrants. Like most songbirds, ovenbirds are territorial and return to the same areas each year. While in North America, mature hardwood stands are their favorite habitat.

Ovenbirds live in mature deciduous and mixed wood stands**.** They are most numerous where the forest floor is shaded by a thick canopy of trees. Ovenbirds eat insect larvae and worms.

Ovenbirds are vulnerable to predation along the forest's edge. To obtain food and avoid predators, they live in the forest's interior. Furthermore, less forest edge helps to improve the survival of all nesting songbirds (Saskatchewan Interactive). However, the width of forest edge for ovenbird is not known with certainty (Dawson *et al.*, 1998).

III. Modelling Description

The model is constructed using system dynamics methodology, an effective tool in dealing with dynamic problems (such as deforestation in tropics, chronic high levels of inflation, or in this study, habitat loss) (Forrester, 1968). It is essential in system dynamics methodology that model structure should provide a valid description of the real system (Forrester *et al.*, 1980; Barlas, 1996). The purpose in a system dynamics modeling study is, typically, to reveal how and why the problematic behavior is generated and to find leverage points in the system, which are effective in eliminating the problematic behavior. These leverage points is then used to generate ‘policies’ (such as tax regulations) to improve the situation.

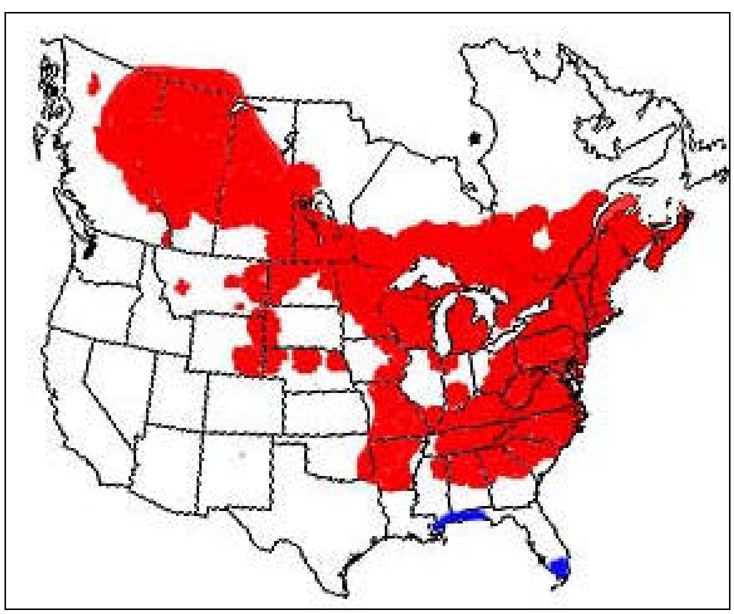

Figure 2. Breeding distribution of the ovenbird (Red areas on the map) (Nearctica, 2001).

The main building blocks of a formal system dynamics model are stocks, flows and converters. Stocks (symbolized by rectangles) are also known as levels or state variables. They represent major accumulations in the system. Flows (symbolized by valves), also known as rates, change the value of stocks. In turn, stocks in a system determine the values of flows. Flows represent activities that fill in or drain the stocks. Intermediate concepts or calculations are known as converters. Converters are computed from stocks, constants, data, and other converters unless they are constants (HPS, 1996). The focus and the time frame of the study are crucial in deciding which elements of the system is to be represented as stocks, flows or converters.

For example, populations of young and adult birds (young_females, adult_females, wintering_young_females, wintering_adult_females) are modelled as stocks in the stock-flow structure of the model (Figure 3). The processes acting upon these populations (reproduction, death, migration_YF, migration_AF, winter_death) are represented as flows. The variables that are used in the calculation of these flows such as Carrying_capacity and maturation_adj_time are converters. The full model equations are provided in the Appendix at the end of the paper.

After extensive literature survey, two bird species are selected as indicator species for two land classes: Eastern Meadowlark (*Sturnella magna*) for grassland habitats and Ovenbird (*Seiurus aurocapillus*), an already threatened species, for forest habitats. A systemic model was developed which is applicable for both species. However, it considers only the population dynamics and related relationships with no spatial emphasis. The model then integrated with a hypothetical land use data using spatial modeling environment software, SME to add the spatial dimension to the analysis. This, apart from being a rather novel approach, makes possible to carry out analysis that is more realistic and reach results that are more reliable.

For the model presented in this paper, a hypothetical landscape consisting of 100 × 100 cells was used. Each cell is 30 m × 30 m. The hypothetical land use map has a number of land uses ranging from grassland to high intensity residential in accordance with NLCD land cover class definitions. The crucial point about the maps is that they should have sufficiently fine resolution to be able to represent and analyse the study region effectively. The quantitative system dynamics model, once completed and validated, was integrated with land-use map of that is needed by the model during simulation. Each model will run for each pixel sequentially. The model runs for each pixel sequentially. In addition to the communication amongst the model sectors, there is interaction between neighbouring pixels. The nature of this interaction is mostly physical due to spatial continuity (i.e. migration). It is worth noting pixels are artificial structures and they are a means of spatial derivation devised for ease of analysis. The pixel interaction within the model is presented in Figure 4. It considers the effect of *land use change* on migration. The *land use change* and *habitat* affects *population dynamics*. *population dynamics* in the target pixel together with the corresponding variables of neighbouring pixels may cause *emigration* or *immigration* from the pixel to its neighbours through population dynamics.

Evidently, the *land use changes* in neighboring pixels affect the *population dynamics* in the target pixel.

III.I. Main Assumptions

There are twelve major assumptions of the model:

- The ratio between female and male birds was assumed 1:1.
- Only female birds are considered in the model.
- Maturation period was assumed 12 months for both species.
- Only mature (adult) birds migrate between neighboring cells.
- Simulation starts on January 1th.
- Minimum Habitat Size was assumed 10 ha for both eastern meadowlark and ovenbird (Hull, 2000; Fitzgerald *et al.*, 2000; Kobal *et al.*, 1998). This was accomplished roughly but satisfactorily by the use of edge habitat formulation.
- Deaths occurring during seasonal migrations are not taken into account due to lack of information (Moore *et al.*, 1995).
- Differences between agricultural lands are not considered such as conventionally tilled or no-tilled fields, mowing etc.
- Spatial differences in vegetative species, vegetation height, moisture or different management practices within the same land uses are not considered.
- Only land use map was used in the study.
- It was assumed that individual birds return to the same breeding ground every year (Hull, 2000).
- Cowbird parasitism was included inclusively in the edge habitat and habitat suitability index formulations (Hull, 2000; Podolsky, 2000; Sherry *et al.*, 1995).

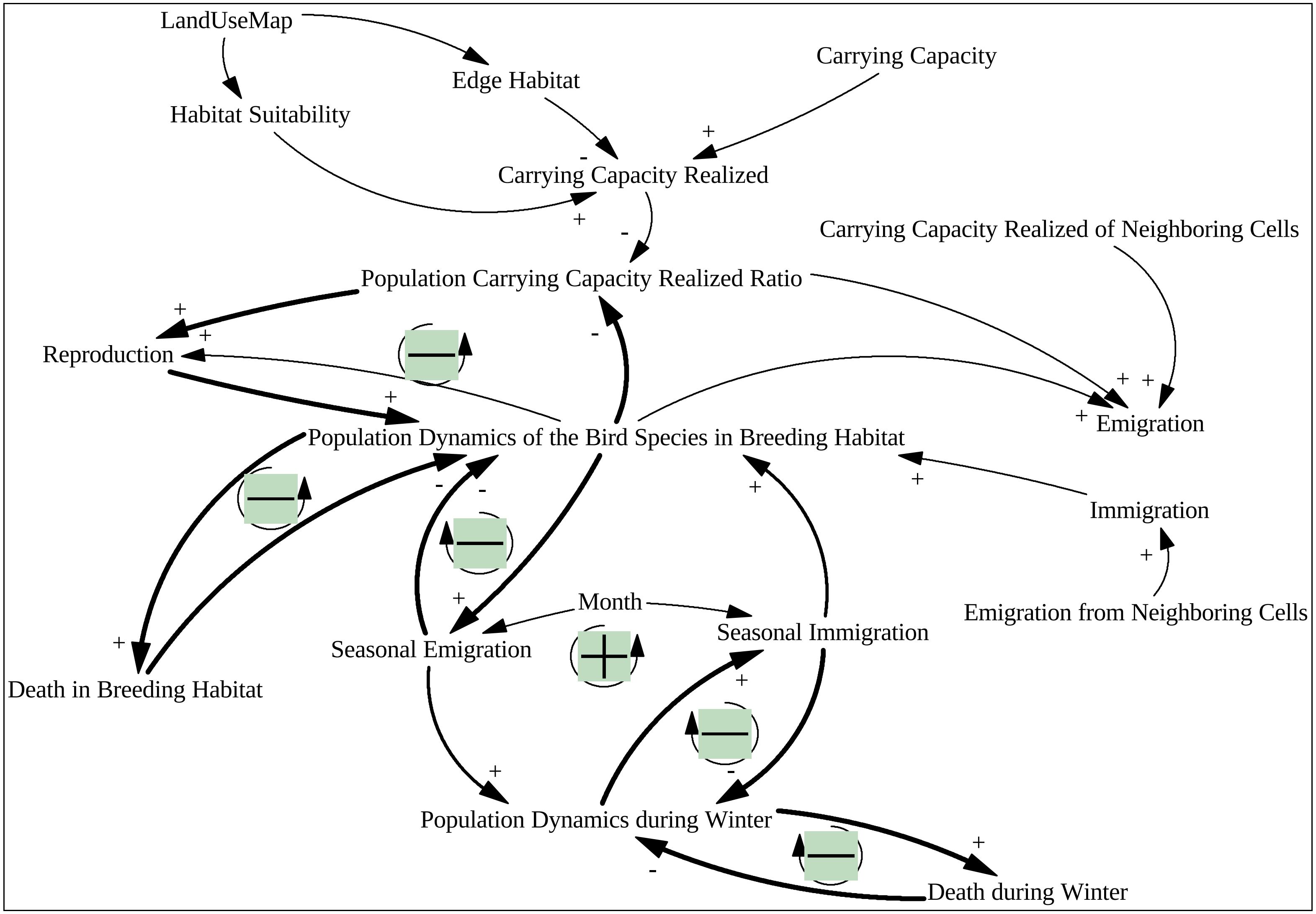

Figure 3. Broad Causal Loop Diagram.

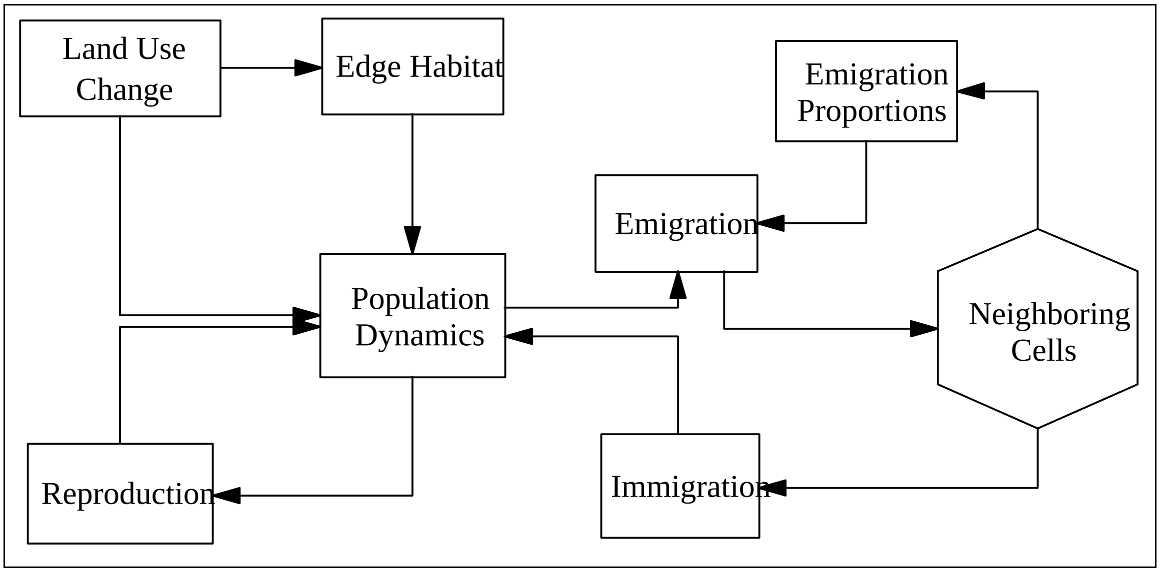

Figure 4. Sectors Diagram of the Model.

III.II. Broad Causal Loop Diagram

In system dynamics modeling, causal loop diagrams give a straightforward representation of the whole model and help to identify the major feedback mechanisms in the system under study.

The core of the model is the population dynamics of the species. The population in breeding habitat is the focal point of the study and hence, it is the part of the model where everything boils down. The land use pattern at a particular cell and whether it is located in edge habitat dictate the realized carrying capacity for that cell. The realized carrying capacity may be lower than or equal to the maximum carrying capacity. Maximum carrying capacity is the carrying capacity in grassland for eastern meadowlark or in forest for ovenbird (i.e. the most suitable habitats for these species). Land use patterns in the particular cell and in its neighbouring cells are used in finding out whether that cell is an edge habitat or not.

The ratio between the population and realized carrying capacity affects both reproduction and emigration rates. If the ratio is low then reproduction is encouraged, emigration is discouraged and visa versa. Reproduction increases population while death decreases. These variables form two negative (goal-seeking) feedback loops (Figure 3). There is another negative feedback loop formed by population in breeding habitat with seasonal emigration. The population in breeding habitat is also affected by the immigration from neighbouring cells.

A similar structure holds for population in wintering habitat except the absence of reproduction and the ratio between the population and realized carrying capacity. The reason for the absence is obvious for the first one and lack of sufficient knowledge on the wintering grounds of the species for the latter.

The negative feedback loops are coupled with a positive feedback loop formed by populations in breeding and wintering habitat, seasonal emigration, and seasonal immigration.

Emigration from the cell is dictated by the ratio between the population and realized carrying capacity, the population in breeding habitat and realized carrying capacities of the neighbouring eight cells. On the other hand, immigration is the total emigration from eight neighbouring cells to this particular cell.

The model and its sectors are described in more detail in the following section.

III.III. Model Sectors

There are seven sectors in the model. The relationships between these sectors and also neighbouring cells are shown in Figure 4. Each variable begins with capital letter B in the model to signal that they belong to the bird sub-model of the larger project. However, in this paper they are presented without the capital letter for simplicity.

In the model sectors, some variables values/equations are different for the two bird species. These variables take on the value depending on the value of *GrL_F_Species*, which is a control variable to switch the model from one species to another. If it is 1 the model simulates for the grassland species; if 2, for the forest species.

III.III.I. Land Use Change

This sector contains variables related to land use. Land use patterns and changes may be due to both anthropogenic and non-anthropogenic sources. *LandUseMap* reads the land class from the land use map. *l u index* is a boolean variable; it is 1 if the land class is suitable and zero if it is totally unsuitable (i.e. carrying capacity for that land class is zero). *Habitat Suitability Index* (HSI) takes on values from 0 to 1 depending on the land class (Table 1). HSI values for land use classes that are not listed in the table are zero for both species. The more suitable land class the higher the value for *Habitat Suitability Index*. Though calculated in the Edge Habitat sector *edge index* is also used in this sector since edge habitat hinges on land use change (Figure 5).

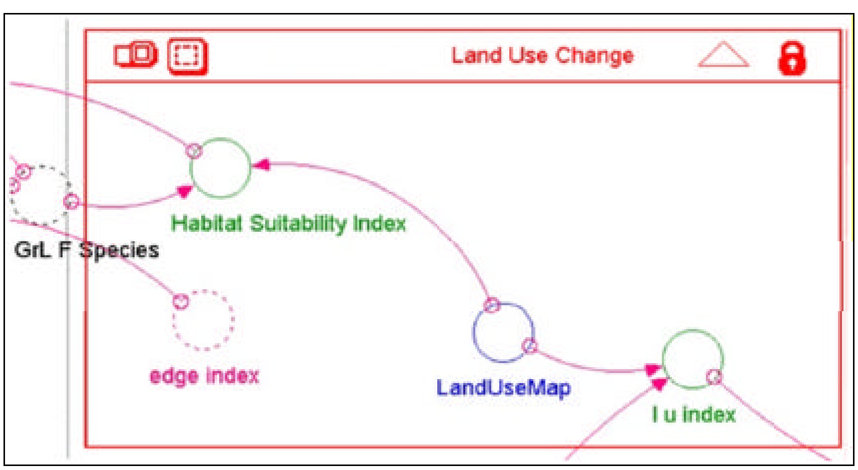

Figure 5. Land Use Change Sector.

Table 1. Habitat Suitability Index Values (HSIV) for eastern meadowlark and ovenbird for different land use classes (HSIV for land use classes that are not listed in the table are zero for both species.) based on Hull, 2000.

habitat suitability index	Indicator Bird Species	
Land Use Class	Eastern Meadowlark	Ovenbird
21 Low Intensity Residential	0.2	0.0
41 Deciduous Forest	0.0	1.0
42 Evergreen Forest	0.0	1.0
43 Mixed Forest	0.0	1.0
51 Shrubland	0.2	0.0
61 Orchards/Vineyards/Other	0.2	0.0
71 Grasslands/Herbaceous	1.0	0.0
81 Pasture/Hay	0.8	0.0
82 Row Crops	0.6	0.0
83 Small Grains	0.6	0.0
84 Fallow	0.3	0.0

III.III.II. Edge Habitat

Edge formulation in the model is a practical way to deal with edge habitat, minimum habitat requirement and suitable habitat shape (i.e. a narrow rectangular habitat is less suitable than a square one with the same area) notions (Faaborg *et al.*, 1995).

Edge habitat is a simple sector used in examining whether the particular cell is in edge habitat and if so where it is located within the edge habitat. Everywhere within an edge habitat does not support the same number of species so it is important to know where that particular cell is located. For a cell to be edge habitat, it should have a land class suitable for the bird species (i.e. *l u index* is 1). It was assumed that the edge habitat is 180 m (i.e. 6 cells) in width (Norment *et al.*, 1999; Dawson *et al.*, 1998) and the cell is marked from 0 to 6, the value of *edge index*. *Edge index* is zero if the cell is not in the edge habitat and it takes values from 1 to 6 depending on the location of the cell within the edge habitat. If at least one of the cell’s eight neighbours is in an unsuitable land class (i.e. the cell borders with an unsuitable land class), the value of *edge index* is 1 and it increases up to 6 as one moves away from the border and toward the interior of the suitable habitat. To determine the value of *edge index*, *l u index* and *edge index* values of the neighbouring cells must also be known (Figure 6).

For most of the grassland bird species, the minimum habitat size is 10 ha and it is 5 ha for eastern meadowlark (Kobal *et al.*, 1998; Hull, 2000). The edge and habitat structures are modelled based on these observations. Also for ovenbird, Dawson *et al.* suggests that forest area should be greater than 30 ha and edge index formulation is modified for ovenbird according to this observation.

Dawson *et al.* states that the depth of forest edge habitat is greater than 100 m so it seems 180 m is a reasonable conservative estimate for the width of edge habitat for ovenbird in the model.

III.III.III. Emigration and Emigration Proportions Sectors

total emigration from a cell is determined by the breeding adult population, *adult_females*, *emigration rate*, which is between 0 and 1.

total emigration = emigration_rate*Adult_Females

Emigration rate is a graphical function of the ratio between population and realized carrying capacity (*Over_under_CC_realized*) (Figure 7). Hence, *Over_under_CC_realized* is simply a measure of crowding pressure on the population.

However, how to distribute these emigrates to the neighboring cells depends on their realized carrying capacities (*CC_realized*). The number of emigrates to each direction is found by, for example for north direction,

to_N = proportion_N * total_emigration

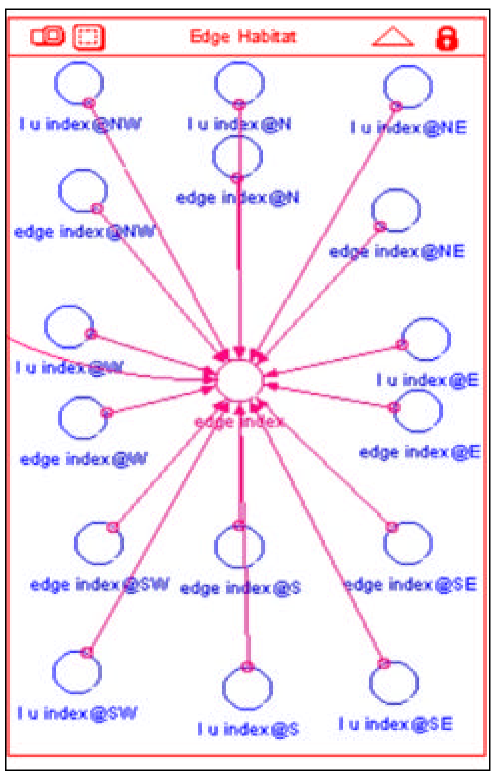

Figure 6. Edge Index Sector.

The proportion of emigrates that will go in each direction is, again for north direction,

proportion_N = CC_realized@N / total_CC_realized

where,
CC_realized@N is the realized carrying capacity of the neighbouring cell at north of the target cell and,
total_CC_realized is the sum of realized carrying capacity values of the eight neighbouring cells (Figure 8).

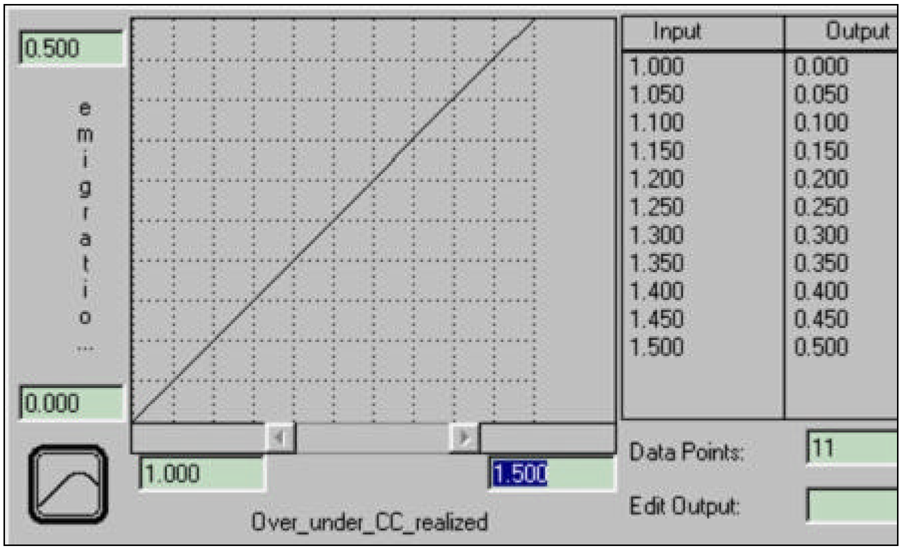

Figure 7. The graphical *emigration rate* function.

III.III.IV. Immigration Sector

The total number of immigrants is calculated in this sector. Simply, the immigrants from each neighboring cell, e.g. *to_N@S* are summed to find the total number of immigrants arriving into the cell, *total immigration* (Figure 9). The mathematical expression for this variable is,

total_immigration=to_W@E+to_S@N+to_SW@NE+to_SE@NW+to_N@S+to_NW@SE+to_NE@SW+to_E@W

III.III.V. Reproduction Sector

In this sector, the number of young immature birds survived and recruited into the population is calculated. This number depends on a number of factors. Primarily it depends on the number of adult females. There is also a nesting success rate, which is a graphical function of, again the ratio between population and realized carrying capacity (*Over_under_CC_realized*). Its value changes between 0 and 1 (Figure 10). An adult female eastern meadowlark attempts to nest up to four times until she nests and breeds two times during a breeding season (McCoy *et al.*, 1999). Ovenbird female attempts to nest up to two times until she nests and breeds one time during a single breeding season (Podolsky, 2000). *total successful nesting attempts* reflects this aspect and it is simply the number of successful nests that produced youngsters in a breeding season and hence is a function of *adult female population* and *nesting success rate* (McCoy, 1999; Podolsky, 2000; Lanyon 1957).

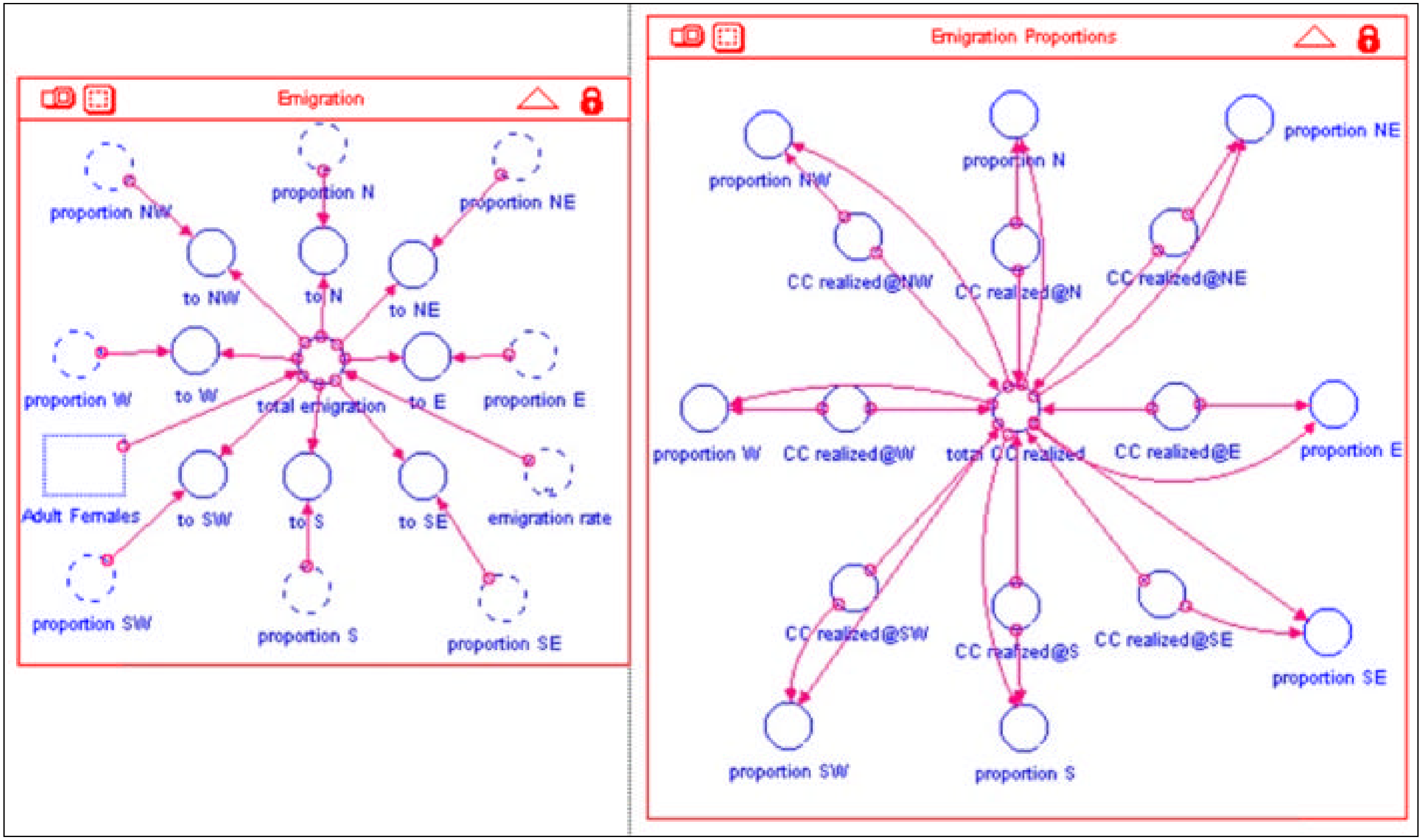

Figure 8. Emigration and Emigration Proportions Sectors.

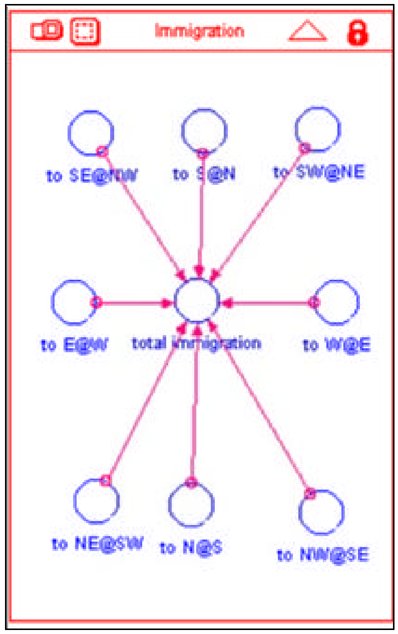

Figure 9. Immigration Sector.

Hence, the mathematical expression for this variable is,

total_successful_nesting_attempts = if GrL_F_Species=1 then (Adult_Females *((nesting_success_rate)+(nesting_success_rate^2)+2*(nesting_success_rate^2*(1-nesting_success_rate))+3*(nesting_success_rate^2*(1-nesting_success_rate)^2) +(nesting_success_rate*(1-nesting_success_rate))+(nesting_success_rate*(1-nesting_success_rate)^2)+(nesting_success_rate*(1-nesting_success_rate)^3))) else if GrL_F_Species=2 then (Adult_Females*nesting_success_rate*(2-nesting_success_rate)) else 0

total successful nesting attempts is multiplied by *young females per nest* (2 for eastern meadowlark (McCoy *et al.*, 1999), 1.84 for ovenbird (Podolsky, 2000; Lanyon, 1957)) to get the total number of female youngsters hatched and survived in a breeding season. This number then uniformly distributed throughout the entire breeding season. The breeding season for eastern meadowlark is from third week of April to second week of August (Norment *et al.*, 1999; Lanyon, 1957); for ovenbird it is from the end of May until August (Conservation Commission of Missouri Report). *young females per nest* reflects the number of female youngsters that are hatched and survived, they are not the number of eggs laid or hatched per nest per se (Figure 11):

recruited_young_females = if GrL_F_Species=1 then (if MOD(time,12)>=3.75 and MOD(time,12)<=7.25 then (total_successful_nesting_attempts*young_females_per_nest /3.75) else 0) else if GrL_F_Species=2 then (if MOD(time,12)>=5 and MOD(time,12)<7 then (total_successful_nesting_attempts*young_females_per_nest/2) else 0) else 0

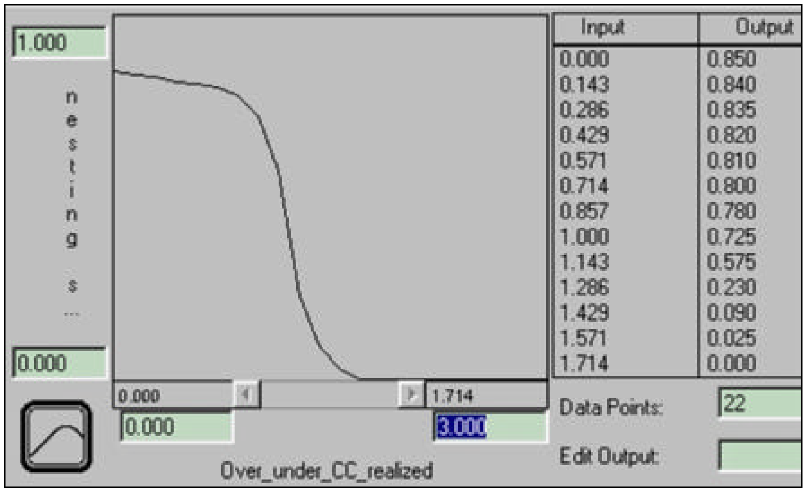

Figure 10. The graphical nesting success rate function.

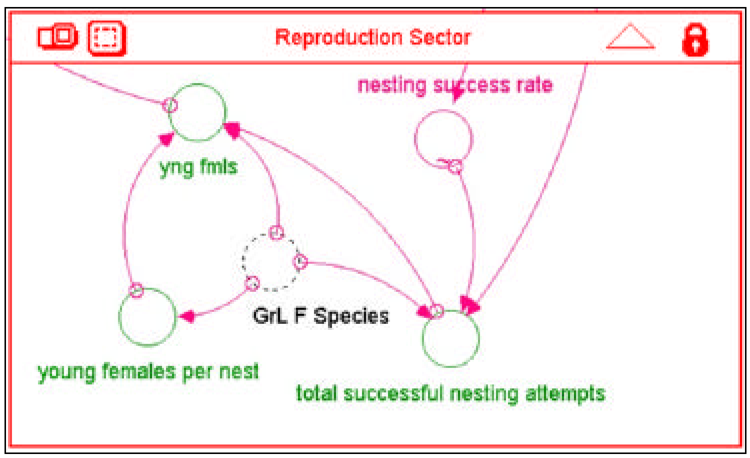

Figure 11. Reproduction Sector.

III.III.VI. Population Dynamics

This is the most important and most complicated sector of the model. The (maximum) *carrying capacity* for ovenbird is 0.043 based on data from Smith *et al.*, 1987. It is assumed 0.025 for eastern meadowlark based on the available literature (Vickery *et al.*, 1999; Winter, 1999).

The simulation is assumed to start on January 1^{th}. Hence, the initial population levels, *Pop Initial* are zero in breeding habitat stocks and 0.008 in wintering stocks for both young and adult females for eastern meadowlark. They are zero in breeding habitat stocks and 0.01 in wintering stocks for both young and adult females for ovenbird. The initial wintering population levels are calibrated to obtain stable oscillations in population level.

The reproduction is simulated in the Reproduction sector and the death rates are straightforward. The death rate of adult females is a graphical function of *Over_under_CC_realized*. There are two graphical death rate functions in the model, one for grassland species (eastern meadowlark) based on McCoy *et al.* (1999), one for forest species (ovenbird) based on Podolsky (2000). They are similar and the graphical death rate function for grassland species is presented in Figure 12 as an example. The death rate of young females is twice that of adults (McCoy *et al.*, 1999). *CC_realized* is the real carrying capacity of the cell found by multiplying the (maximum) *carrying capacity* with a fraction depending on the value of *edge index*:

B_CC_realized = if B_GrL_F_Species=1 then (B_Carrying_Capacity*(if B_edge_index=0 then 1 else if B_edge_index=1 then .05 else if B_edge_index=2 then .1 else if B_edge_index=3 then .25 else if B_edge_index=4 then .5 else if B_edge_index=5 then .7 else if B_edge_index=6 then .8 else 1)) else if B_GrL_F_Species=2 then (B_Carrying_Capacity*(if B_edge_index=0 then 1 else if B_edge_index=1 then 0.01 else if B_edge_index=2 then 0.01 else if B_edge_index=3 then .01 else if B_edge_index=4 then .05 else if B_edge_index=5 then .25 else if B_edge_index=6 then .75 else 1)) else 0

Adult Females has an outflow named *imm_emm*, which is the net migration per month. There is a flow from *Young Females* to *Adult Females* called *maturation* and maturation period; *maturation adj time* is assumed 12 months for both species. However, this is a highly generalized approach. It may be calibrated to suit better for the chosen species (Figure 13).

There are seasonal migrations between wintering and breeding habitats. Although eastern meadowlark is not a neo-tropical species, it also migrates to south of the United States to winter. Therefore, there are bi-directional migration flows to represent this situation, *Migration YF* for the young female stock, *Migration AF* for the adult female stock. Migration periods for eastern meadowlark are from the end of February until the end of May during spring and from the end of August until the end of November during fall (Hull, 2000; Lanyon, 1957). Migration periods for ovenbird are from the end of February until the end of April during spring and from the end of September until the end of November during fall (BirdSource, 2001). The mathematical expressions for the seasonal migrations are,

B_Migration_AF = if B_GrL_F_Species=1 then (if MOD(time,12)>=2 and MOD(time,12)<5 then (B_Wintering_Adult_Females/1) else if MOD(time,12)>=8 and MOD(time,12)<11 then (-B_Adult_Females/1) else 0) else if B_GrL_F_Species=2 then (if MOD(time,12)>=2 and MOD(time,12)<4 then (B_Wintering_Adult_Females/1) else if MOD(time,12)>=9 and MOD(time,12)<11 then (-B_Adult_Females/1) else 0) else 0

B_Migration_YF = if B_GrL_F_Species=1 then (if MOD(time,12)>=2 and MOD(time,12)<5 then (B_Wintering_Young_Females/1) else if MOD(time,12)>=8 and MOD(time,12)<11 then (-B_Young_Females/1) else 0) else if B_GrL_F_Species=2 then (if MOD(time,12)>=2 and MOD(time,12)<4 then (B_Wintering_Young_Females/1) else if MOD(time,12)>=9 and MOD(time,12)<11 then (-B_Young_Females/1) else 0) else 0

There are stocks for the wintering period (*Wintering Young Females*, *Wintering Adult Females*) and they have only death flow. The death rate for the adult is 0.05 and it is 0.1 for the young. It is taken constant due to lack of knowledge about their wintering grounds and hence winter population dynamics. The losses during the migration are also not taken into account. The winter death rates are approximately the average death rates in the breeding habitat. The total population at any time is stored in *Population* for the breeding habitat or *Wintering Population* for the wintering grounds depending on the time of the year. They reflect the whole population (i.e. the sum of young and adult female bird numbers multiplied by two.), not only the sum of adult and young females. Note that these variables are not used in any function regarding the population in the model. Those functions are calibrated to work with the number of total females, namely with the half of the total population.

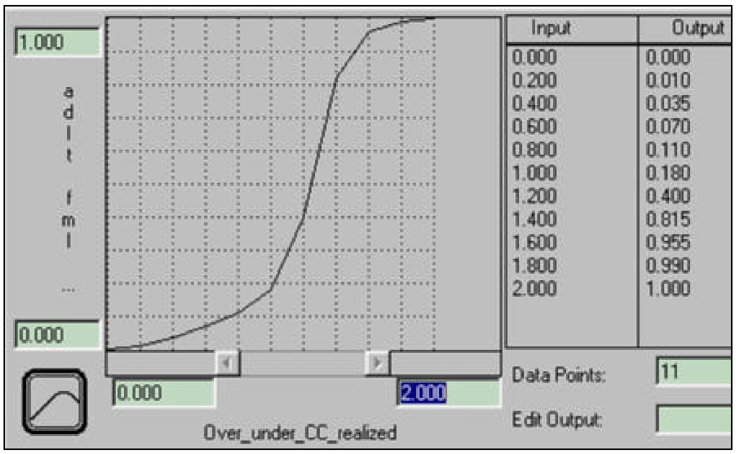

Figure 12. The adult female death rate graphical function.

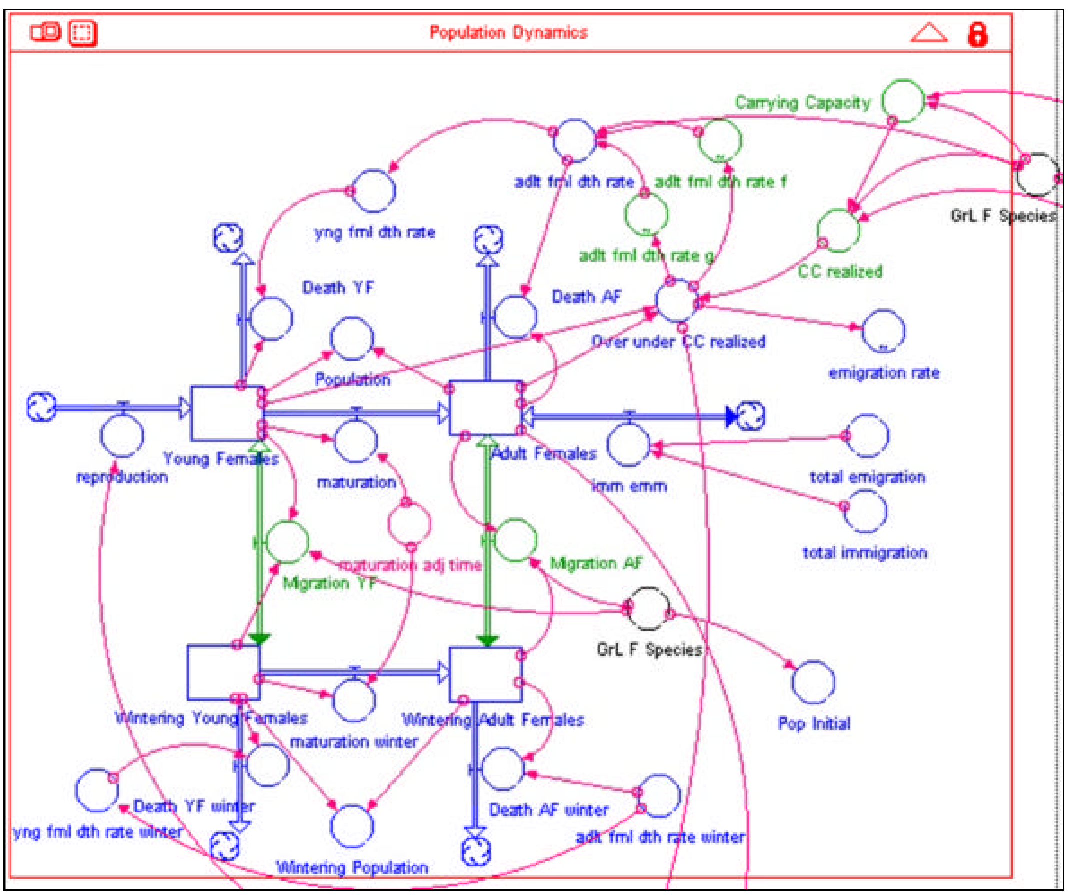

Figure 13. Population Dynamics Sector.

IV. Validation and Analysis of the Model Results

System dynamics models deals with the underlying causes that creates the problematic dynamics in a system. Proper investigation of how and why those problematic dynamics arise depends on a valid structural representation of the system. For this reason, structural validity has foremost importance in system dynamics studies. Unless the structure is adequately represented, the generated behaviour, regardless of how well it fits to the real data, is irrelevant. This is not to say that behavioural validation is ignored but to evaluate the behavioural validity of the model first it has to be structurally valid. Hence, the purpose of the model presented in this paper is not to predict the number of adult bird population at some point in time but to assess the vulnerability of the bird species to habitat loss in their breeding grounds. Furthermore, the model serves under the greater LEAM model to explore what conditions produce severe habitat loss and examine strategies to reduce and even stop it (Barlas 1996; Sterman, 2000).

The non-spatial model was tested to carry out validation tests before integrating with the spatial database. Although the 'behavior validation' of the model with respect to real data is important only the structural validation tests are presented in this section since there exists no long-term population dynamics data compatible with the time horizon of the model. Nor is it possible to collect such long-term field data within the scope of this research. As an example, Figures 14-15 illustrate the 'extreme' behavior of the system when land suitability is zero. In Figure 14, the behavior of the variables population in breeding habitat (1), and wintering population (2); and in Figure 15 (b) the behavior of the adult female (1), and young female populations (2) are demonstrated. According to this 'extreme condition' run, population level drops down to zero as expected.

The indirect structure tests revealed that the model structure yields meaningful behavior under extreme parameter values and model behavior exhibits meaningful sensitivity to the parameters. These are consistent with the empirical and theoretical evidence, offered in literature such as Price et al., 1995; Donovan et al., 1995; Moore et al., 1995; Kobal et al., 1999. In the next section, the model base run behavior is analyzed.

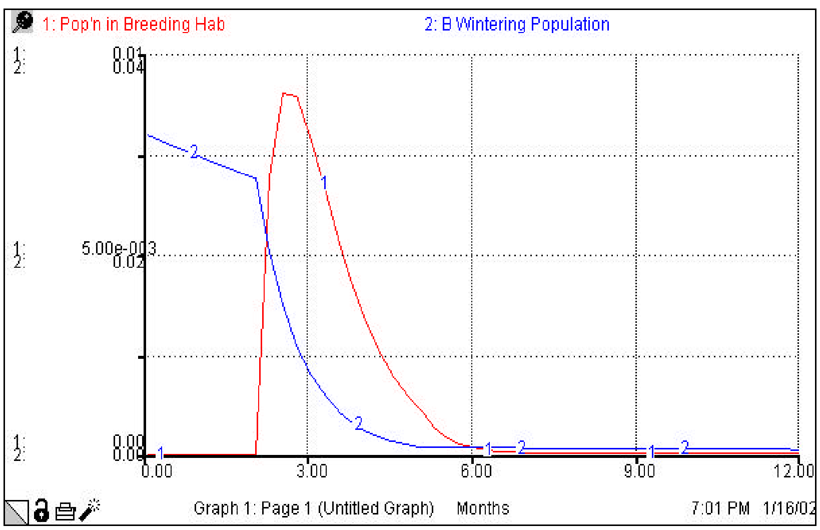

Figure 14. Model behavior when land suitability is zero.

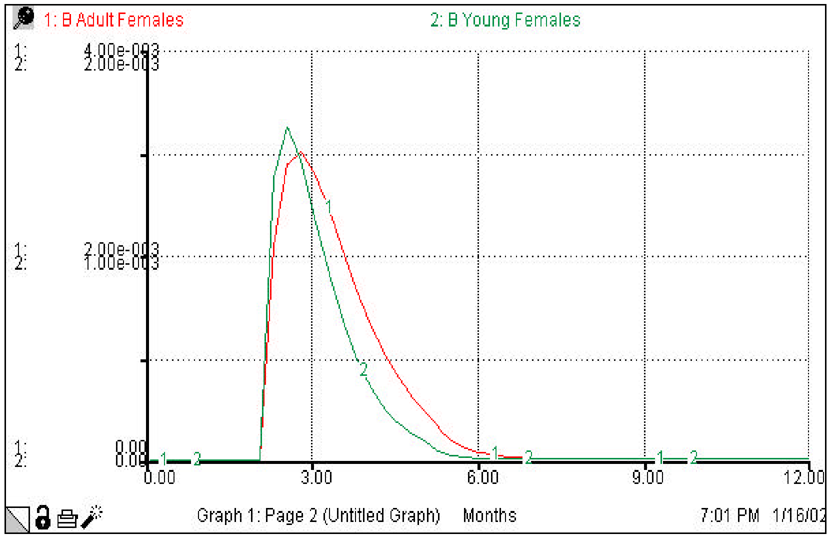

Figure 15. Model behavior when land suitability is zero.

V. Analysis of Results

The non-spatial model was run for both species. Figures 16 and Figures 17 are sample output from the non-spatial base runs for eastern meadowlark, grassland species and for ovenbird, forest species, respectively. The time step (*dt)* for the simulation runs is quarter of a month and time unit is a month.

Populations of both bird species exhibit stable oscillations around 0.03 and 0.04, for eastern meadowlark and ovenbird respectively (Figures 16-17). These equilibrium values are in agreement with figures given in several studies in the literature (Donovan et al., 1995; Lanyon, 1957). The population diminishes and drops down to zero as the birds leave their breeding grounds during fall months and gradually increases as they arrive from their wintering grounds during spring. The shaper increase observed in the middle of spring is due to breeding. Correspondingly, their wintering population increases during fall and diminishes during spring. The gradual decrease in wintering population during winter months is due to the mortality. Since breeding occurs only in summer net death rate in wintering grounds is equal to mortality.

After the non-spatial analysis, the model is integrated with the hypothetical dynamic landscape. The landscape data consists of 20 consecutive maps, each corresponding a particular month. The landscape has several land classes initially. However, in subsequent maps a typical urban sprawl case is imitated where agricultural and other open lands are consumed by the urban expansion each month. These landscape maps served as input for the system dynamics model. Since the landscape changes the carrying capacity and breeding capability of the bird species changes accordingly. This determines the fate of the species in a particular cell.

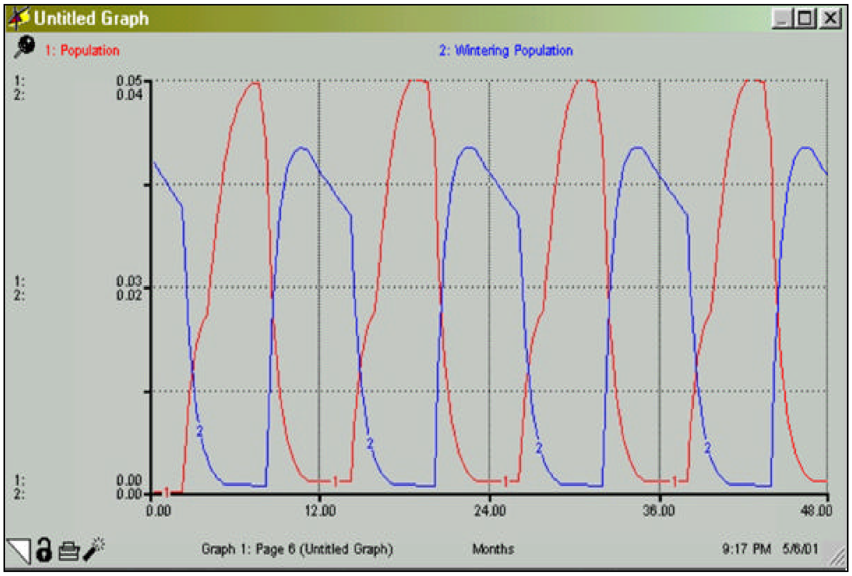

Figure 16. Eastern Meadowlark Population and Wintering Population dynamics for 48 months (4 years).

Figure 17. Ovenbird Population and Wintering Population dynamics for 48 months (4 years).

Figures 18-19 are sample snapshots from spatial simulation. Figure 18 shows the edge habitat map of eastern meadowlark. The carrying capacity is very low in light green areas and increases towards interior (i.e. towards red areas and blue areas surrounded by the red).

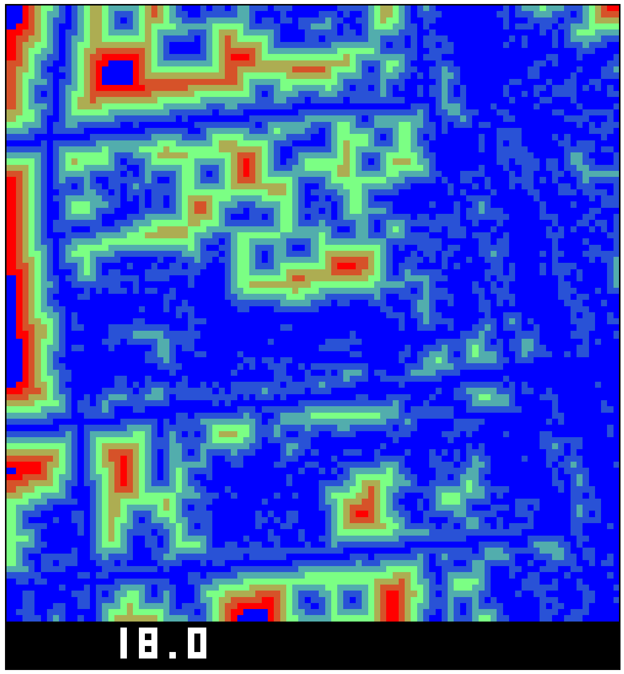

Figure 18. Snapshot of edge habitat map for eastern meadowlark.

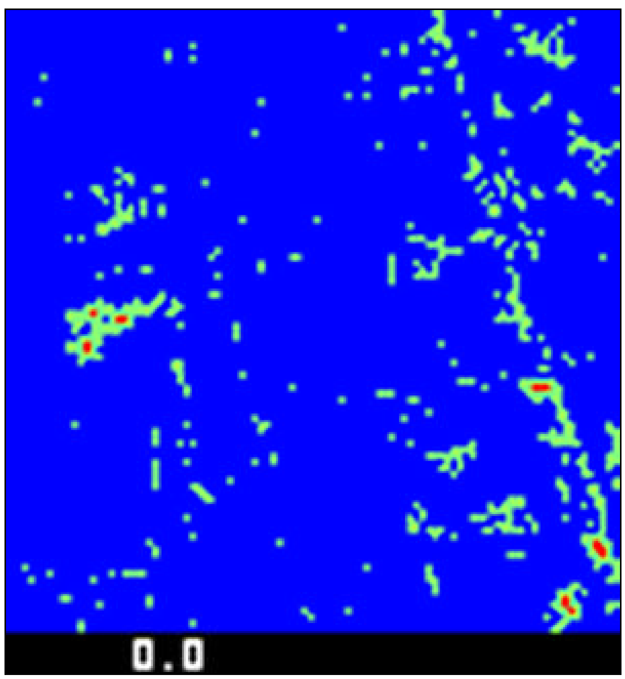

Figure 19. Snapshot of edge habitat map for ovenbird.

Figure 19 is the edge habitat map for ovenbird. There is some suitable habitat for the species but they are all located in the edge. The species is highly negatively affected in edge habitats; hence, their population is always zero throughout the sample study area.

It is obvious from the simulation runs that urban sprawl leads to habitat loss for both species. They are unable to live and breed in residential and industrial areas. For eastern meadowlark, agricultural fields and for ovenbird small forest patches offer little or no protection. What is more, the spatial modelling enabled to represent the edge habitat concept appropriately. This is important since the spatial arrangement of the suitable habitats should be recognized in order to reach meaningful and realistic results. Hence, it is crucial to conserve large areas of native habitat for these bird species to sustain in the face of ever-growing urban areas.

Food sources are not included in the model since it was impossible to incorporate the intimate relations between the bird species and their food sources in a meaningful way in the confines of this study. In addition, there is almost no data on this subject. It is also the same for the predators of these birds. Therefore in this version of the model the bird species have no impact on the ecosystems they belong to. Horizontal and vertical species interaction on the food chain may significantly alter the results.

The policy implication of this study is in accordance with the main concerns of LEAM framework. That is urban sprawl is destructive to the natural environment and it must be replaced by smart growth where the development is to the benefit of both the wildlife and people simultaneously and the use of lands is made in a most efficient way.

VI. Final Remarks and Further Research

Spatial characteristics of species' habitat must be adequately addressed in ecological studies to reach more realistic results and to make efficient use of insights gained from these studies in land use decision-making. It is now possible to construct spatially explicit models with the advance of computer technology and geographic information systems. These advances allow constructing ecological models that are capable of simulating both on spatial and temporal domains. The integration of spatial dimension into the study increases the descriptive power of the model and enhances the relevancy of the proposed policies to the real life. This improvement is crucial for land use managers and decision makers who need accurate information to develop efficient policy options.

In spite of lack of data and hence inadequate validation, the model performs quite satisfactorily both in non-spatial and spatial environments. In fact, it can be regarded as a prototype for more improved and complex models to be constructed in the future. However there is still a need for more data on the ecology of these bird species and their interaction with their habitat. In addition, it should be noted that interspecies relations are not considered in this modelling study. Horizontal and vertical species interaction on the food chain may significantly alter the results.

Brown-headed cowbird parasitism may be included exclusively in the future but it is included indirectly in the edge habitat and habitat suitability index formulations (Hull, 2000; Podolsky, 2000; Sherry *et al.*, 1995).

The bird model presented in this paper is an integral part of the LEAM model platform. It performs within the regional model as an indicator of the effects of probable land-use changes in the Kane County on the native bird species. An interactive version of the large-scale regional model with its social, economic, and ecological components is available on the web (http://www.rehearsal.uiuc.edu/leam/). The regional model is an experimental simulation platform where different aspects of urban development and land-use changes can be explored where the social, economic, and ecological components interact simultaneously.

The spatial habitat modelling is still a novel approach and their success partly depends on the availability of relevant and sufficient data. There is still much to improve in this field and it Is realistic to expect great contributions to the scientific and practical theory from spatial dynamic modelling in the future (Dunning *et al.*, 1995; Turner *et al.*, 1995; Holt *et al.*, 1995).

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Appendix: The Model Equations

The variables representing attributes in neighbouring cells are assigned default values.

```
B_edge_index = if time<99999 then (if B_l_u_index=1 then (if
(B_l_u_index@E=0 or B_l_u_index@N=0 or B_l_u_index@NW=0 or
B_l_u_index@SW=0 or B_l_u_index@S=0 or B_l_u_index@SE=0 or
B_l_u_index@NE=0 or B_l_u_index@W=0) then 1 else if (B_edge_index@E=1
or B_edge_index@N=1 or B_edge_index@NW=1 or B_edge_index@SW=1 or
B_edge_index@S=1 or B_edge_index@SE=1 or B_edge_index@NE=1 or
B_edge_index@W=1) then 2 else if (B_edge_index@E=2 or B_edge_index@N=2
or B_edge_index@NW=2 or B_edge_index@SW=2 or B_edge_index@S=2 or
B_edge_index@SE=2 or B_edge_index@NE=2 or B_edge_index@W=2) then 3 else
if (B_edge_index@E=3 or B_edge_index@N=3 or B_edge_index@NW=3 or
B_edge_index@SW=3 or B_edge_index@S=3 or B_edge_index@SE=3 or
B_edge_index@NE=3 or B_edge_index@W=3) then 4 else  if
(B_edge_index@E=4 or B_edge_index@N=4 or B_edge_index@NW=4 or
B_edge_index@SW=4 or B_edge_index@S=4 or B_edge_index@SE=4 or
B_edge_index@NE=4 or B_edge_index@W=4) then 5 else  if
(B_edge_index@E=5 or B_edge_index@N=5 or B_edge_index@NW=5 or
B_edge_index@SW=5 or B_edge_index@S=5 or B_edge_index@SE=5 or
B_edge_index@NE=5 or B_edge_index@W=5) then 6 else 0) else 0) else 0
B_edge_index@E = 0
B_edge_index@N = 0
B_edge_index@NE = 0
B_edge_index@NW = 0
B_edge_index@S = 0
B_edge_index@SE = 0
B_edge_index@SW = 0
B_edge_index@W = 0
B_l_u_index@E = 1
B_l_u_index@N = 1
B_l_u_index@NE = 1
B_l_u_index@NW = 1
B_l_u_index@S = 1
B_l_u_index@SE = 1
B_l_u_index@SW = 1
B_l_u_index@W = 1
B_total_emigration = B_emigration_rate*B_Adult_Females
B_to_E = B_proportion_E*B_total_emigration
B_to_N = B_proportion_N*B_total_emigration
B_to_NE = B_proportion_NE*B_total_emigration
B_to_NW = B_proportion_NW*B_total_emigration
B_to_S = B_proportion_S*B_total_emigration
B_to_SE = B_proportion_SE*B_total_emigration
B_to_SW = B_proportion_SW*B_total_emigration
B_to_W = B_proportion_W*B_total_emigration
B_CC_realized@E = .025
B_CC_realized@N = .025
B_CC_realized@NE = .025
B_CC_realized@NW = .025
```

```
B_CC_realized@S = .025
B_CC_realized@SE = .025
B_CC_realized@SW = .025
B_CC_realized@W = .025
B_proportion_E = B_CC_realized@E/B_total_CC_realized
B_proportion_N = B_CC_realized@N/B_total_CC_realized
B_proportion_NE = B_CC_realized@NE/B_total_CC_realized
B_proportion_NW = B_CC_realized@NW/B_total_CC_realized
B_proportion_S = B_CC_realized@S/B_total_CC_realized
B_proportion_SE = B_CC_realized@SE/B_total_CC_realized
B_proportion_SW = B_CC_realized@SW/B_total_CC_realized
B_proportion_W = B_CC_realized@W/B_total_CC_realized
B_total_CC_realized =
B_CC_realized@E+B_CC_realized@N+B_CC_realized@NE+B_CC_realized@NW+B_CC_
realized@S+B_CC_realized@SE+B_CC_realized@W+B_CC_realized@SW
B_Habitat_Suitability_Index = if B_GrL_F_Species=1 then (If
B_LandUseMap=11 or B_LandUseMap=12 or B_LandUseMap=22 or
B_LandUseMap=23 or B_LandUseMap=31 or B_LandUseMap=32 or
B_LandUseMap=33 or B_LandUseMap=41 or B_LandUseMap=42 or
B_LandUseMap=43 then 0 else if B_LandUseMap=21 then 0.2 else If
B_LandUseMap=51 then 0.2 else if B_LandUseMap=61 then 0.2 else if
B_LandUseMap=71 then 1 else if B_LandUseMap=81 then 0.8 else if
B_LandUseMap=82 or B_LandUseMap=83 then 0.6 else if B_LandUseMap=84
then 0.3 else if B_LandUseMap=85 then 0.0 else 0) else if
B_GrL_F_Species=2 then (if B_LandUseMap=41 or B_LandUseMap=42 or
B_LandUseMap=43 then 1.0 else 0.0) else 0
B_LandUseMap = 71
B_l_u_index = if B_GrL_F_Species=1 then (if B_LandUseMap=21 or
B_LandUseMap=51 or B_LandUseMap=61 or B_LandUseMap=71 or
B_LandUseMap=81 or B_LandUseMap=82 or B_LandUseMap=83 or
B_LandUseMap=84 or B_LandUseMap=85 then 1 else 0) else if
B_GrL_F_Species=2 then (if B_LandUseMap=41 or B_LandUseMap=42 or
B_LandUseMap=43 then 1 else 0) else 0
B_total_immigration =
B_to_W@E+B_to_S@N+B_to_SW@NE+B_to_SE@NW+B_to_N@S+B_to_NW@SE+B_to_NE@SW+
B_to_E@W
B_to_E@W = 0
B_to_N@S = 0
B_to_NE@SW = 0
B_to_NW@SE = 0
B_to_S@N = 0
B_to_SE@NW = 0
B_to_SW@NE = 0
B_to_W@E = 0
B_Adult_Females(t) = B_Adult_Females(t - dt) + (B_maturation +
B_imm_emm + B_Migration_AF - B_Death_AF) * dt

INIT B_Adult_Females = 0
B_maturation = B_Young_Females/B_maturation_adj_time
B_imm_emm = (B_total_immigration-B_total_emigration)
B_Migration_AF = if B_GrL_F_Species=1 then (if MOD(time,12)>=2 and
MOD(time,12)<5 then (B_Wintering_Adult_Females/1) else if
MOD(time,12)>=8 and MOD(time,12)<11 then (-B_Adult_Females/1) else 0)
else if B_GrL_F_Species=2 then (if MOD(time,12)>=2 and MOD(time,12)<4
then (B_Wintering_Adult_Females/1) else if MOD(time,12)>=9 and
MOD(time,12)<11 then (-B_Adult_Females/1) else 0) else 0
B_Death_AF = B_Adult_Females*B_adlt_fml_dth_rate
```

```
B_Wintering_Adult_Females(t) = B_Wintering_Adult_Females(t - dt) +
(B_maturation_winter - B_Migration_AF - B_Death_AF_winter) * dt

INIT B_Wintering_Adult_Females = B_Pop_Initial
B_maturation_winter = B_Wintering_Young_Females/B_maturation_adj_time
B_Migration_AF = if B_GrL_F_Species=1 then (if MOD(time,12)>=2 and
MOD(time,12)<5 then (B_Wintering_Adult_Females/1) else if
MOD(time,12)>=8 and MOD(time,12)<11 then (-B_Adult_Females/1) else 0)
else if B_GrL_F_Species=2 then (if MOD(time,12)>=2 and MOD(time,12)<4
then (B_Wintering_Adult_Females/1) else if MOD(time,12)>=9 and
MOD(time,12)<11 then (-B_Adult_Females/1) else 0) else 0
B_Death_AF_winter =
B_Wintering_Adult_Females*B_adlt_fml_dth_rate_winter
B_Wintering_Young_Females(t) = B_Wintering_Young_Females(t - dt) + (-
B_maturation_winter - B_Death_YF_winter - B_Migration_YF) * dt

INIT B_Wintering_Young_Females = B_Pop_Initial
B_maturation_winter = B_Wintering_Young_Females/B_maturation_adj_time
B_Death_YF_winter = B_Wintering_Young_Females*B_yng_fml_dth_rate_winter
B_Migration_YF = if B_GrL_F_Species=1 then (if MOD(time,12)>=2 and
MOD(time,12)<5 then (B_Wintering_Young_Females/1) else if
MOD(time,12)>=8 and MOD(time,12)<11 then (-B_Young_Females/1) else 0)
else if B_GrL_F_Species=2 then (if MOD(time,12)>=2 and MOD(time,12)<4
then (B_Wintering_Young_Females/1) else if MOD(time,12)>=9 and
MOD(time,12)<11 then (-B_Young_Females/1) else 0) else 0
B_Young_Females(t) = B_Young_Females(t - dt) + (B_reproduction +
B_Migration_YF - B_maturation - B_Death_YF) * dt

INIT B_Young_Females = 0
B_reproduction = B_yng_fmls
B_Migration_YF = if B_GrL_F_Species=1 then (if MOD(time,12)>=2 and
MOD(time,12)<5 then (B_Wintering_Young_Females/1) else if
MOD(time,12)>=8 and MOD(time,12)<11 then (-B_Young_Females/1) else 0)
else if B_GrL_F_Species=2 then (if MOD(time,12)>=2 and MOD(time,12)<4
then (B_Wintering_Young_Females/1) else if MOD(time,12)>=9 and
MOD(time,12)<11 then (-B_Young_Females/1) else 0) else 0
B_maturation = B_Young_Females/B_maturation_adj_time
B_Death_YF = B_Young_Females*B_yng_fml_dth_rate
B_adlt_fml_dth_rate = if B_GrL_F_Species=1 then B_adlt_fml_dth_rate_g
else if B_GrL_F_Species=2 then B_adlt_fml_dth_rate_f else 0
B_adlt_fml_dth_rate_winter = 0.05
B_Carrying_Capacity = if B_GrL_F_Species=1 then
(0.025*B_Habitat_Suitability_Index) else if B_GrL_F_Species=2 then
(0.043*B_Habitat_Suitability_Index) else 0
B_CC_realized = if B_GrL_F_Species=1 then (B_Carrying_Capacity*(if
B_edge_index=0 then 1 else if B_edge_index=1 then .05 else if
B_edge_index=2 then .1 else if B_edge_index=3 then .25 else if
B_edge_index=4 then .5 else if B_edge_index=5 then .7 else if
B_edge_index=6 then .8 else 1)) else if B_GrL_F_Species=2 then
(B_Carrying_Capacity*(if B_edge_index=0 then 1 else if B_edge_index=1
then 0.01 else if B_edge_index=2 then 0.01 else if B_edge_index=3 then
.01 else if B_edge_index=4 then .05 else if B_edge_index=5 then .25
else if B_edge_index=6 then .75 else 1)) else 0
B_maturation_adj_time = 12
B_Over_under_CC_realized = if B_CC_realized=0 then 10 else
((B_Adult_Females+B_Young_Females)/B_CC_realized)
```

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B_Pop_Initial = if B_GrL_F_Species=1 then 0.008 else if
B_GrL_F_Species=2 then 0.01 else 0.0
B_Wintering_Population =
2*(B_Wintering_Adult_Females+B_Wintering_Young_Females)
B_yng_fml_dth_rate = B_adlt_fml_dth_rate*2
B_yng_fml_dth_rate_winter = 2*B_adlt_fml_dth_rate_winter
Pop'n_in_Breeding_Hab = 2*(B_Adult_Females+B_Young_Females)
B_adlt_fml_dth_rate_f = GRAPH(B_Over_under_CC_realized)
(0.00, 0.00), (0.2, 0.01), (0.4, 0.015), (0.6, 0.035), (0.8, 0.085),
(1.00, 0.18), (1.20, 0.4), (1.40, 0.815), (1.60, 0.955), (1.80, 0.99),
(2.00, 1.00)
B_adlt_fml_dth_rate_g = GRAPH(B_Over_under_CC_realized)
(0.00, 0.00), (0.2, 0.01), (0.4, 0.035), (0.6, 0.07), (0.8, 0.11),
(1.00, 0.18), (1.20, 0.4), (1.40, 0.815), (1.60, 0.955), (1.80, 0.99),
(2.00, 1.00)
B_emigration_rate = GRAPH(B_Over_under_CC_realized)
(1.00, 0.00), (1.05, 0.05), (1.10, 0.1), (1.15, 0.15), (1.20, 0.2),
(1.25, 0.25), (1.30, 0.3), (1.35, 0.35), (1.40, 0.4), (1.45, 0.45),
(1.50, 0.5)
B_total_successful_nesting_attempts = if B_GrL_F_Species=1 then
(B_Adult_Females*((B_nesting_success_rate)+(B_nesting_success_rate^2)+2
*(B_nesting_success_rate^2*(1-
B_nesting_success_rate))+3*(B_nesting_success_rate^2*(1-
B_nesting_success_rate)^2)+(B_nesting_success_rate*(1-
B_nesting_success_rate))+(B_nesting_success_rate*(1-
B_nesting_success_rate)^2)+(B_nesting_success_rate*(1-
B_nesting_success_rate)^3))) else if B_GrL_F_Species=2 then
(B_Adult_Females*B_nesting_success_rate*(2-B_nesting_success_rate))
else 0
B_yng_fmls = if B_GrL_F_Species=1 then (if MOD(time,12)>=3.75 and
MOD(time,12)<=7.25 then
(B_total_successful_nesting_attempts*B_young_females_per_nest/3.75)
else 0) else if B_GrL_F_Species=2 then (if MOD(time,12)>=5 and
MOD(time,12)<7 then
(B_total_successful_nesting_attempts*B_young_females_per_nest/2) else
0) else 0
B_young_females_per_nest = if B_GrL_F_Species=1 then 2 else if
B_GrL_F_Species=2 then 1.84 else 0
B_nesting_success_rate = GRAPH(B_Over_under_CC_realized)
(0.00, 0.85), (0.143, 0.84), (0.286, 0.835), (0.429, 0.82), (0.571,
0.81), (0.714, 0.8), (0.857, 0.78), (1, 0.725), (1.14, 0.575), (1.29,
0.23), (1.43, 0.09), (1.57, 0.025), (1.71, 0.00), (1.86, 0.00), (2.00,
0.00), (2.14, 0.00), (2.29, 0.00), (2.43, 0.00), (2.57, 0.00), (2.71,
0.00), (2.86, 0.00), (3.00, 0.00)
B_GrL_F_Species = 1
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