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Agent-based modeling of movements and habitat selection by mid-continent mallards

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Agent-based modeling of movements and habitat selection by mid-continent mallards

Final Report for a Natural Resource Conservation Service Conservation Effects Assessment Project (Grant No. NR183A750023C003)

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Executive summary

The Wetland Reserve Easements program administered by the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) provides landowners with support and incentives to protect and enhance wetlands on private land. These wetland easements constitute an important foraging resource for waterfowl. Management of easements for the benefit of waterfowl populations depends on understanding waterfowl responses to habitat conditions, which may be based on complex and emergent interactions between behavioral, environmental, and anthropogenic factors. We conducted an agent-based modeling approach intended to help guide decisions on the acquisition of new easement parcels and management of existing easements, with the aim of maximizing forage benefits for wintering waterfowl populations. We focused the model on a representative location in the Mississippi Alluvial Valley (MAV) and on the most common dabbling duck species wintering in the region, the mallard (*Anas platyrhynchos*). We addressed the following three objectives: 1) development of an agent-based model of waterfowl bioenergetics, foraging behavior, and movement during the wintering season; 2) simulation of wintering waterfowl population responses to landscape composition and configuration changes that represent alternative future conservation scenarios under a range of environmental variability; and 3) evaluation of the contribution of current NRCS wetland easements to waterfowl populations in the MAV, including identification of future conservation scenarios that are most likely to benefit wintering waterfowl.

To address objective 1, we used SWAMP (Spatially explicit Waterbird Agent-based Model Program), an agent-based model previously created for waterbirds in the Central Valley of California. SWAMP simulates waterfowl foraging, energetics, and behavior on a JAVA platform, using Geographic Information System (GIS) maps of extant landscapes that have been categorized into habitat types of interest. Agents representing waterfowl move within the landscape, foraging on areas made available conditional on a configurable inundation status, and depleting food resources. Agent characteristics and behavior as well as landscape parameters were used to simulate desired waterfowl species, habitat configurations, and flooding conditions. We simulated 212,500 mallards over a period of 120 days (1 November – March 2) in a large-scale region (~29,000 km^2) located in east-central Arkansas, chosen for its representative habitat configuration, number of existing conservation easements, and availability of model validation data.

For objective 2, we developed a suite of conservation scenarios that represented different management actions centering around current and future NRCS easement amount and configurations. Scenarios encoded a range of variations of existing easement conditions (increase or decrease of food availability, localized changes in flooding regimes), or addition and/or restoration of further wetlands to easement holdings (i.e., establishing new easements or rounding out existing ones at opportunistic or selected locations). Different environmental conditions outside the control of active management were combined with these scenarios in the form of global changes of flooding conditions, simulating weak or severe drought conditions or unusually high precipitation/inundation. Simulations were run at high replication with randomly changing landscape flooding patterns to generate a representative image of the possible outcome space.

To address objective 3, we chose median population abundance across replicates at the end of the simulated period (day 120) as the principal metric to characterize benefits to waterfowl carrying capacity offered by each conservation scenario. We identified a small number of fundamental management questions and evaluated scenario performance in the context of these questions, constructing rankings of the simulated management approaches while considering the dynamics of further metrics of interest (e.g., stored lipids, energy budgets, time proportion spent in different foraging habitats).

We found that the absence of existing conservation measures would reduce wintering mallard population abundance by ~70-80%, underlining the importance of current wetland easements for waterfowl foraging. Simulated management approaches were only effective under standard (average) or moderately lower inundation conditions, while even intensive management approaches made little difference under unusually high-flood or strong drought conditions. However, active flooding (stored water release) considerably increased carrying capacity under strong drought conditions. Under standard conditions, the partial active flooding of easements later in the season and upgrading of unmanaged wetlands to managed status provided the best results. Scenarios that enhanced the quality or availability of wetlands in existing easements generally yielded greater gains in end-of-season population abundance than scenarios that added new easement area with restored wetlands, but benefits from the latter were still considerable. Establishment of entirely new easements with a high percentage of converted crop patches was preferable over rounding out existing easements using any directly contiguous patches. Selecting added easement patches based on proximity to sanctuaries or former wetland character enhanced the effectiveness of rounding out existing easements, but was largely ineffective when establishing new easements.

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Introduction

Since 1990, the Wetlands Reserve Program (WRP) and its successor, the Agricultural Conservation Easement Program (ACEP), administered by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS), have restored and enhanced wetlands on agricultural land and protected existing wetlands as Wetland Reserve Easements to improve wildlife habitats (USDA 2022). The program assists landowners willing to contribute to the availability of waterfowl habitat on private lands. Technical support and financial incentives are provided to encourage landowners to protect or enhance existing wetlands, or restore hydrology to retired farmland. While landowners are not required to apply continued habitat management, conservation easements often improve habitat for waterfowl by providing increased amounts of plant and invertebrate food (Olmstead, Webb, and Johnson 2013). The administration and expansion of reserve easement areas is thus a valuable tool for waterfowl management. This is particularly the case for the large, concentrated populations of birds that collect in wintering grounds.

Landscape conservation and management to sustain waterfowl populations depend on understanding waterfowl responses to habitat conditions, which may be based on complex and emergent interactions between behavioral, environmental, and anthropogenic factors (Gray et al. 2013; Kaminski and Elmberg 2014). An assessment of the potential benefits and drawbacks of alternative approaches to restore wetlands in terms of areas, configurations, and conditions could inform future conservation planning. Such assessments may assist in identifying how and where conservation easements might be best allocated in the future to serve migratory birds as well as the broad range of biota dependent most effectively upon wetland systems. In addition, this information can help evaluate the contribution of current NRCS wetland easements to waterfowl conservation as well as inform future conservation planning.

A well-established method to assist planning efforts for waterfowl habitat management in non-breeding areas is the use of bioenergetics models. Such models are used to estimate the energetic carrying capacity of habitats, or the time period that food resources in a landscape could sustain a given waterfowl population. In its most basic form, this type of model estimates carrying capacity as “duck energy-days” (DEDs) by calculating the ratio of total food energy available in the landscape to daily energy expenditure of the total bird population (Williams et al. 2014). Landscape conditions can then be characterized by their provision of a variable number of DEDs, and management practices can be evaluated by their capacity to enhance this value. DED models are widely used and readily applied at large scales due to their modest data requirements. However, DED models are subject to a number of limitations in that they treat a waterfowl population as a single unit, ignoring individual behaviors and emergent effects of inter-individual interactions; they do not incorporate spatial heterogeneity; and they describe only the basic metrics of energy supply and demand without representing other factors that determine waterfowl interaction with habitat, such as daily energy and time budgets, body condition, mortality, and variable energy costs for different activities (Williams et al. 2014). These drawbacks limit the use of DED models for generating reliable estimates of carrying capacity in response to management actions, which at landscape scale may have relatively subtle or heterogeneous effects.

Agent-based models (ABMs) provide an alternative modeling approach that can represent behavior of landscape-forager systems. The system's dynamics emerge from the interaction of individual actors (agents) with each other and with their shared habitat, thus providing a bottom-up rather a top-down representation (Grimm and Railsback 2005; Miller et al. 2014). ABMs allow spatially explicit representation of habitat data and agent behavior, enabling explicit inferences about individual-level metrics such as habitat selection and movement patterns in response to food availability; integrate effects at the individual levels at group or population levels, allowing the simulation of emergent effects at multiple scales; and, due to their real-time simulation nature, enable the tracking of the change of time of many parameters with potentially revealing dynamics, such as trends in body condition over the course of the simulation period. ABMs are computationally expensive, but scale well and allow users to employ a much larger range of informative inputs than simpler models (Grimm and Railsback 2005).

We employed an ABM to model waterfowl foraging behaviors, movements, body condition, and distribution in a well-parametrized landscape during the wintering period. Our main aim was to assess the relative effects of a range of conservation and management approaches, centered around the NRCS easement program, in increasing landscape potential to sustain a waterfowl population over the course of the season. In the interest of high-quality parameterization, we chose a single representative location that was of sufficient scale to encompass the expected local and regional movement range of the most representative wintering waterfowl species in the region, the mallard (*Anas platyrhynchos*; Beatty et al. (2014)). Across most of the wintering range for waterfowl in the Mississippi Flyway, half or more of the total number of wintering waterfowl consists of mallards (USFWS 2016), making this species a suitable representative for general waterfowl dynamics in the region. We selected a location in the Mississippi Alluvial Valley (MAV) region of the Mississippi Flyway wintering range (east-central Arkansas) because of the region's exceptional importance for wintering ducks (Soulliere et al. 2013; USFWS 2016), the availability of local observational data sets for model validation (Krementz, Asante, and Naylor 2012; Beatty et al. 2014) and because the area had both a habitat composition highly representative of the MAV in general and contained a large number of conservation easements.

The project had the following objectives:

1) <u>Develop an agent-based model of waterfowl bioenergetics, foraging behavior, and movement during the wintering season</u>

To address Objective 1, we required a model environment capable of simulating a substantial number of individuals on a large-scale map (212,500 mallards on ~30,000 km^2; see Methods). We developed a new version of SWAMP (Spatially-explicit Waterbird Agent-based Modeling Program), previously developed for waterbirds in the Central Valley of California (Miller et al. 2014). As an agent-based modeling platform, SWAMP offered a number of advantages: it was created as a dedicated waterfowl ABM implementing a great number of specialized mechanics and parameters of importance to the model; it has the capacity to simulate large numbers of agents at large spatial scales; it is under active development, with new functionalities and parameterization continuously being added; and the developers were interested in cooperating with us in the creation of features of special interest for our project.

Briefly, SWAMP is an ABM of waterfowl foraging, energetics, and behavior implemented in the MASON multi-agent simulation software (Luke et al. 2005). The model simulates real-world landscapes using existing maps that have been categorized into

habitat types of interest. Agents representing waterfowl move within the landscape, foraging on areas that are made available conditional on a configurable inundation status and depleting food resources. Agent characteristics and behavior as well as landscape parameters are provided by the user in configuration files that can be used to shape specific habitat conditions (e.g., inundation status). Summary output metrics relating to the landscape or agents are continually written to file as the simulation period progresses and can then be further processed by the user. A substantial expansion of the published model's functionality (movement decisions at hierarchical spatial scales) was implemented during the course of the project. The model and its inputs are described in Methods sections I (model and agent parameterization) and II (map development and parameterization).

2) Simulate wintering waterfowl population responses to thematic landscape composition and configuration changes that represent alternative future conservation scenarios under a range of environmental variability

To address Objective 2, we developed a suite of conservation scenarios that represented different management actions centering around quantity and configuration of current and future NRCS wetland easements. These scenarios were introduced into the model in the form of variants of the basic habitat map, and encoded as a range of existing easement conditions (increase or decrease of food availability, localized changes in flooding regimes) or addition and/or restoration of wetlands to easement holdings (establishing new easements or rounding out existing ones, at opportunistic or selected locations). Different environmental conditions outside the control of active management were combined with these scenarios in the form of global changes of flooding conditions, simulating weak or severe drought conditions or unusually high precipitation/inundation. All simulations were run at high replication (n = 136), with randomly changing landscape flooding patterns, to generate a representative image of the possible outcome space. Management scenarios and run setups are described in Methods section III.

3) Evaluate the contribution of current NRCS wetland easements to waterfowl populations in the MAV and identify future conservation scenarios that are most likely to benefit wintering waterfowl

To address objective 3, we evaluated simulation results in the context of several questions:

- Compared to a situation where conservation easements are absent, what is the effect of the NRCS conservation easement program at its current extent? Compared to a situation where no management is applied, what is the effect of active wetland management in current easements?
- What is the effect of adding additional existing wetlands and wetlands restored from crop patches to easements, if patches are chosen opportunistically / at random under different environmental conditions? What are the effects of establishing entirely new easements versus rounding out existing easements and of adding this area in smaller or larger units?
- What is the effect of the above if patches are chosen based on additional location criteria (near existing waterfowl refuges, or using only patches recorded as prior wetlands)?
- What is the effect of enhancing the availability or biomass yield of wetlands already present in easements?
- What is the overall most effective approach to increase population numbers sustained by the landscape?

We chose median population abundance across replicates at the end of the simulated period (day 120) as the principal metric to compare the performance of these scenarios. We then constructed rankings of the management approaches, taking into account the dynamics of further metrics of interest (e.g., stored lipids, energy budgets, time proportion spent in different foraging habitats), and identified the most effective method to achieve increased landscape carrying capacity in the context of each question. Simulation results are presented and discussed in the Results section.

Methods

I) Model structure and agent parameterization

A) Model overview

The following is a summary of the structure and functionality of the current version of the model. More details and a structured model definition are provided in Miller et al. (2014). Parameter values used for the described functionalities are discussed in section I C (agents) and II C (landscape).

The model consisted of a modified version of SWAMP (Spatially explicit Waterbird Agent-based Model Program; Miller et al. 2014), which is implemented in Java using MASON (Luke et al. 2005), a library for the development of agent-based, spatially explicit models. The model simultaneously simulates the behavior of a specified number of independent agents foraging on a landscape with dynamic food energy values and availability. It can use algorithmically generated landscapes or make use of imported GIS maps, as was done in the present case. SWAMP was developed to model behavior and energy requirements of dabbling ducks in the Central Valley of California. We have adapted the landscape and agent parameterization specifically for mallards in the Mississippi Alluvial Valley.

The map was made up habitat units based on contiguous map polygons with a uniform set of parameters, referred to as "patches". Patches varied in area, and were distinguished by their habitat type, which determines mean food biomass and energy content, and flooding status (see Methods II D for details). The simulated ecological system represented wetlands and agricultural lands during winter when these habitats are flooded; thus, it was assumed that food biomass is depleted and not restocked during that time period. Initial food biomass was distributed to patches with a defined variance at model initialization (using published mean values and a gamma distribution). Depletion occurred via two processes: food-specific constant decay rates applied to all food items (see section D), and removal of food biomass by foraging agents (see section C).

Agents followed a generalized behavior pattern considered appropriate for wintering dabbling ducks (Miller et al. 2014). Separate parameter sets can be specified for different forager species; in the present model, these parameters were made specific to mallards whenever possible. Simulated birds spent most of the day in refuge areas and dispersed in the afternoon to forage in nearby wetlands and crop fields, returning to roost in refuges following acquisition of sufficient daily food resources. No explicit flocking behavior was implemented, although flocking-like effects emerged from the aggregate behavior of agents. Probability of an agent selecting a specific food patch was proportional to food density on the patch and flight distance. This behavior was implemented as a hierarchical choice system that allows agents to relocate at increasing distance scales in reaction

to decreasing local food resources (see next section (B)). Competition was indirect, in that depletion of food density lowers the probability that another forager will select the same patch; however, a maximum density of agents per patch was observed. If food density fell below a specified giving-up threshold, the patch was no longer considered as a foraging location. Agents switched to a new patch during a foraging bout if they could no longer derive a rate of energy gain greater than their foraging metabolic rate from the current patch (Miller et al. 2014).

Agents could only forage on patches marked as flooded. Flooding status for a given model run was applied probabilistically at the start of the simulation based on each patch's flooding probability, which was derived from satellite data. Thus, replicate runs of the same simulation played out on landscapes with different patterns of available foraging areas, unless this random element was specifically locked in.

The model implemented a fixed number of roosting locations (refuges) on the map. At the end of a foraging bout, agents chose the closest refuge and returned there to roost, dispersing again for the next bout according to the hierarchical patch selection process (see section B). Refuges thus functioned as attractors within the larger landscape parcels defined by the scales of hierarchical relocation. Refuge patches remain forageable.

Foraging activity was governed by a type II functional response modeled using Holling's disc equation (Holling 1959):

$$i = \frac{\alpha' R t}{1 + \alpha' R H_T'} \qquad \text{(Equ. 1)}$$

where i is amount of food eaten, t is elapsed time, α' is an attack constant, R is food density in the patch, and H_T is handling time for a unit of food. The attack constant represents search efficiency (m^2/s). Foragers thus acquired food at a rate proportional to food density, modified by search and handling efficiency. Food energy was processed using a two-stage metabolism model. Following consumption, food energy was directly added to a non-lipid energy reserve, roughly equivalent to blood glucose. At the end of the next roosting period, all remaining non-lipid reserves were moved to the lipid store, which represented body fat, using a set conversion efficiency (Miller and Newton 1999) (i.e., the conversion involves a loss of energy). Metabolic demands were first supplied from non-lipid reserves and then from lipid reserves; if both were depleted, the agent died. Metabolic costs were specified for foraging and non-foraging activities; the latter were treated as one time-weighted average of a number of activities like sleep, courtship, preening, etc. (see Miller et al. 2014 for details). The model employed a consistent time step of 15 minutes during which costs were evaluated and actions carried out.

Agents in the model emigrated out of the landscape if their stored energy level (lipid reserves) dropped below a certain threshold. This threshold was defined as a fraction of the agent's maximum lipid stores and checked before the start of each day's foraging excursion. Thus, emigration would generally preempt death by starvation except in rare cases generated by the model's timing schedule. In a multi-landscape simulation, emigration could trigger transferal of the agent to another region/map; in the present model, emigration removed the agent entirely. The model currently has no representation of hunting disturbance or mortality; thus, all agent movements and exits from the simulation were driven by foraging dynamics.

Model runtime is dependent on the number of simulated agents and size of the map, both of which were substantial in the present case. The model therefore implemented a downscaling method that allowed reducing computation load without

sacrificing data accuracy or resolution. A scaling factor was chosen, then each foraging patch was assigned a "simulated area" that was divided by this factor. The initial number of agents placed on the map and food biomass assigned to each patch was equally scaled down. When agents chose or interacted with patches for foraging, the simulated area was used, but movement distances were still based on unadjusted values. These changes ensure that energetic expenditures and travel times were preserved, but the energetic values of regions and patches were adjusted accurately for a smaller population. Tests with a scaling factor of 1/100 showed that scaling did not affect simulation outcomes, but greatly decreased simulation time.

Figure I.1 shows a schematic overview of the major decision rules, inputs, and outputs of the model. Figure I.2 shows a simplified flowchart of the decisions made by an agent during each time step of the simulation.

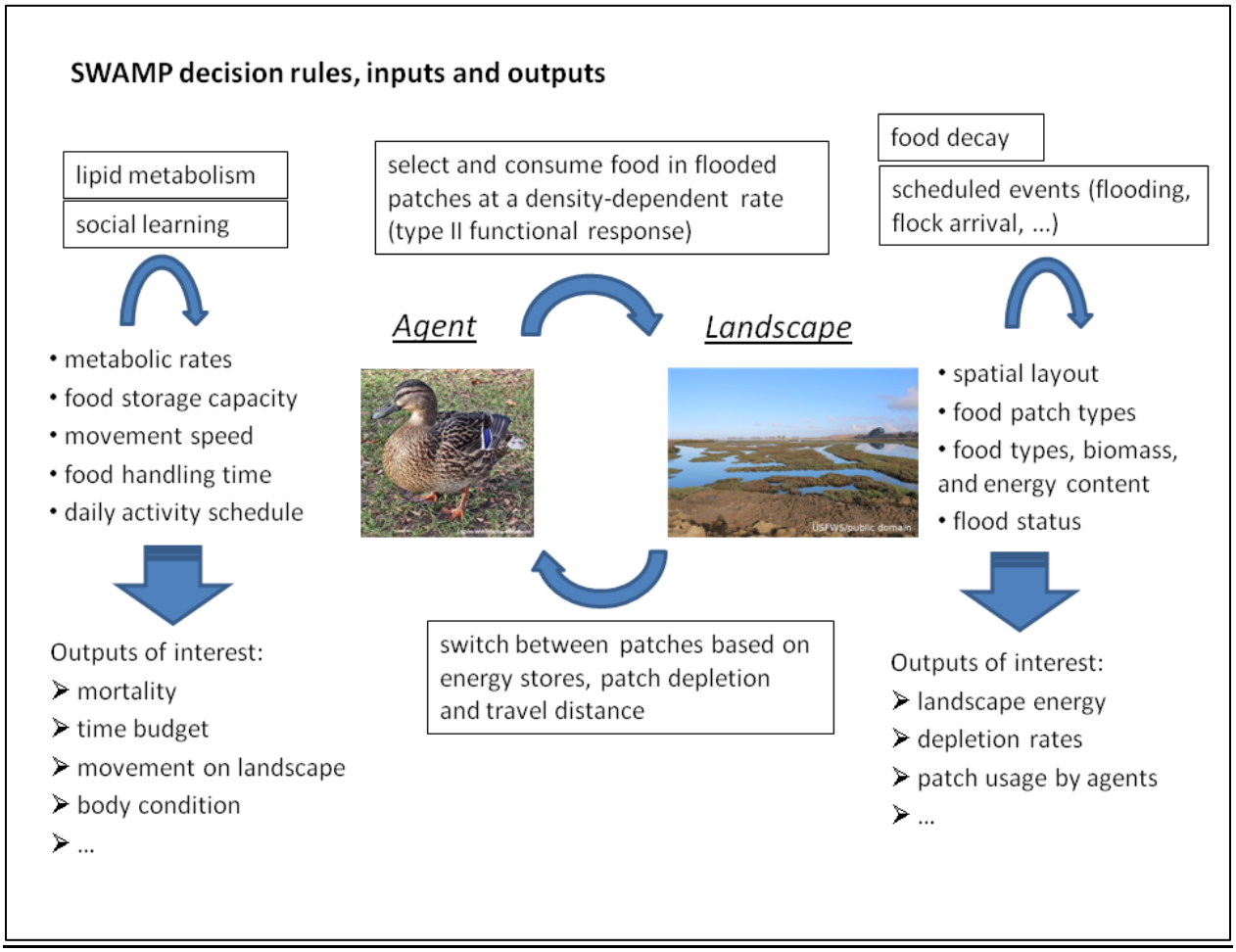


Figure I.1. Major decision rules (boxes), inputs (circle bullets) and outputs (arrow bullets) in the Mississippi Alluvial Valley (MAV) mallard model. SWAMP is the Spatially-explicit Waterbird Agent-based Modeling Program.

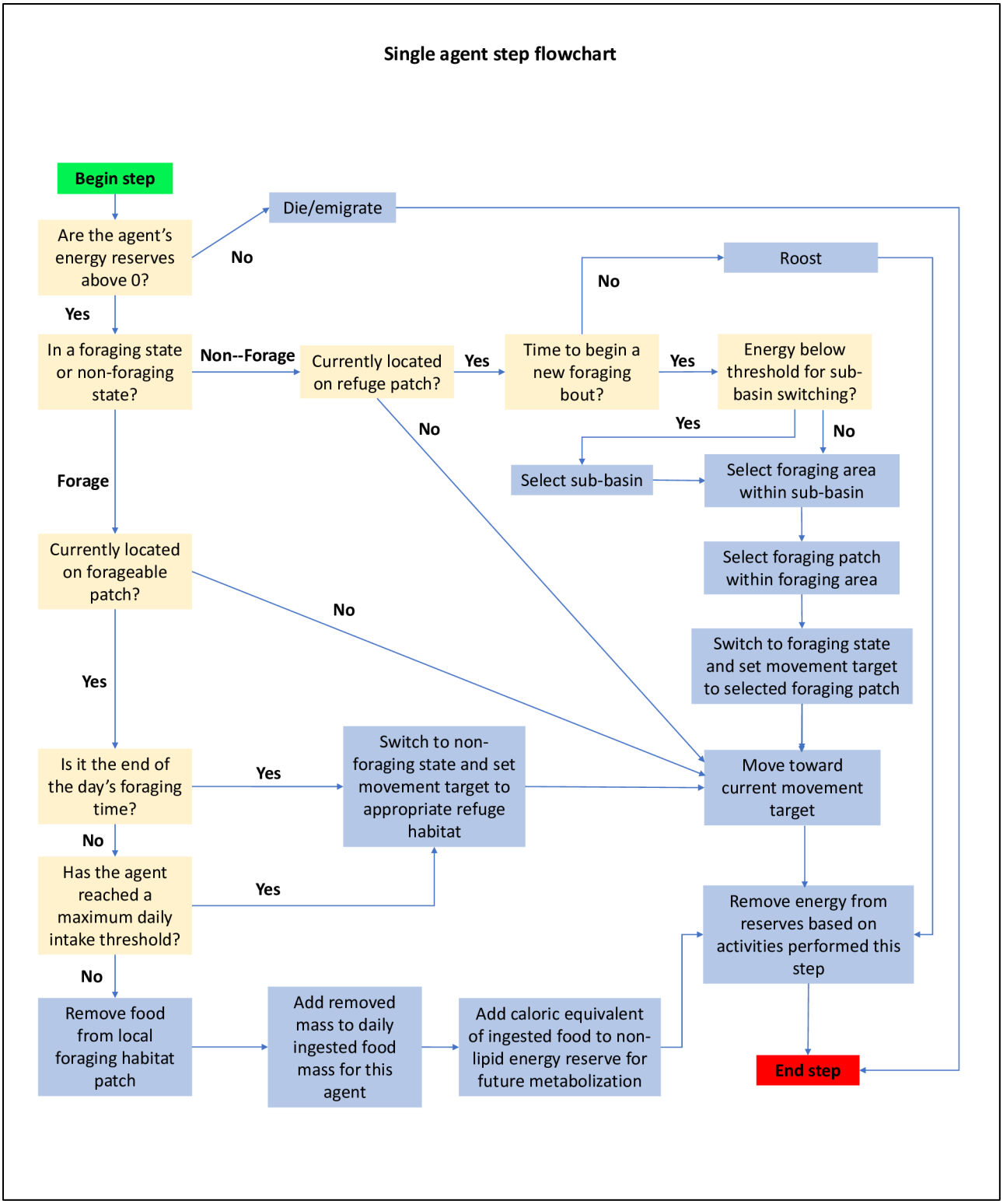


Figure I.2. Flowchart of decisions taken during each time step (15 minutes of simulated time) by a single agent in the Mississippi Alluvial Valley (MAV) mallard model.

B) Hierarchical patch selection

Previous model version

The SWAMP model was initially developed to track the behavior and foraging success of agents on a relatively simple landscape: first, a small grid of patches and, later, a landscape of a single basin (Butte Basin in CA) covering approximately 900 km^2. In these landscapes, each patch with available food and water was theoretically a potential foraging target each day, as the maximum distance between any two patches in the landscape was 62 km.

Patch selection in earlier model versions proceeds as follows. At the beginning of a foraging day, all individuals are located in a roosting habitat. The model builds a matrix with selection weights (W), from each roosting patch to each potential foraging patch (patches with available food and water). The selection weights are defined as

$$W_{ij} = \frac{A_j \times F_j^f}{D_{ij}^d} \qquad \text{(Equ. 2)}$$

where *i* is the initial roost patch, and j is the potential target, A_j is target patch wet area, F_j is the target patch food density, and D_{ij} is the distance between the initial and target patch. The parameters *f* and *d* are exponents determining how strongly agents weight food density and travel distance, respectively, with larger exponents indicating a larger weight of the corresponding factor. Once this matrix of weights is built, each individual agent chooses a target patch by weighted random choice, with the selection probability for each target patch equal to

$$\Pr(\text{Choose } j \mid \text{in } i) = \frac{W_{ij}}{\sum_j W_{ij}} \qquad \text{(Equ. 3)}$$

Individuals also make patch selection decisions when they leave a foraging patch due to either falling below a foraging threshold, or the agent reaching the end of their foraging day and needing to choose a roosting patch. At the end of the foraging day, agents choose the nearest roost patch that has space available for them.

Although this set of patch selection rules worked well for the Butte Basin, which has a relatively limited number of foraging patches, roosts, and agents, two major issues arose when attempting to apply SWAMP to the MAV. The GIS map generated for this MAV model had ~160,000 patches, covering >29,000 km^2, with a maximum distance between patches of 234 km. The MAV model landscape is an order of magnitude larger than the Butte Basin map for which SWAMP was initially developed. Early simulations run in the MAV landscape using previous versions of SWAMP led to 1) huge computer memory usage and very slow model performance, and 2) most or all agents dying of low foraging rates despite there still being a considerable amount of food available on the landscape. Early explorations suggested that due to the localized nature of individuals' foraging decisions, patches near roosts were likely being overexploited, thereby causing individuals to fly further to gather food throughout winter. However, individuals in these models had no mechanism to switch to a roost further away with better quality forage nearby due to the combination of foraging and roost selection rules. Further, the computer memory and computational requirements prevented us from running the model with more roosting sites, which could have potentially allowed for switching to new roosts as nearby foraging patches were depleted.

While the simple set of patch selection rules described above worked well for a relatively small landscape like the Butte Basin, real waterfowl likely do not make foraging patch selection decisions in this way. It is unlikely that individuals would consider all possible foraging patches up to hundreds of kilometers away on equal terms. There is a significant body of research suggesting that foraging patch selection in wintering waterfowl is a hierarchical process in which decisions are made at broad scales initially and then focus on increasingly smaller scales (Johnson 1980; Baldassarre and Bolen 1994; Davis et al. 2014; Kaminski and Elmberg 2014). Waterfowl first make selections of 1) large geographic regions, before selecting 2) specific wetland complexes (Beatty et al. 2014). Birds then select 3) wetland patches within the complex, and finally 4) microhabitats within those patches (Johnson 1980). The earlier SWAMP model provides a mechanism for making habitat selection decisions at level 3, and eliminates the need for decisions at level 4, but does not allow for decision-making at levels 1 and 2.

Improved functionality in current model version

Implementing patch selection as a hierarchical decision-making process ameliorates the two major limitations (described above) induced by running the previous version of SWAMP on the MAV landscape. First, it reduces the number of patches that need to be considered in every patch selection decision, thus reducing computer memory usage and number of computations. Second, adding the higher levels of decision making allows agents to remove themselves from areas in which their foraging success is insufficient to maintain a positive energy balance.

In order to implement hierarchical patch selection, broader-level landscape categories were required. Patches were previously the only landscape categorization. In increasing order of area, we introduced Foraging Areas (FA) and Sub-Basins (SB). A FA is an area within which all daily foraging happens (patch switching is confined to a Foraging Area), while a SB is the new broadest scale of landscape categorization (and the level at which agents move if their foraging performance falls too low). Sub-Basins and FAs were defined in the GIS file using hierarchical k-means clustering of patch centroids in QGIS. Patches were first clustered into a number of SBs, then further clustered within each SB into FAs (FAs did not cross SB boundaries). The optimal number of SBs in the landscape, FAs per SB, and patches per FA were determined from output validation tests (see section D).

The hierarchical patch selection algorithm in the new version of SWAMP proceeds as follows. 1) At the beginning of each foraging day, each individual agent assesses whether it should move to a new SB based on the individual's lipid levels. If an individual falls below a defined percentage of their maximum lipid reserve, the individual will move to a new SB, otherwise it will continue its hierarchical patch selection within the same SB.

When an individual chooses to stay within the current roosting SB, 2) it next chooses one of the FAs within that SB. As with patch selection (described previously), FA selection weights *W(FA)* are defined as in Equation 2, replacing *f* and *d* with *f(fa)* and *d(fa)* as exponents determining how strongly agents weight food density and distance in choosing a foraging area. Once this matrix of weights is built, each individual agent chooses a target patch by weighted random choice as in Equation 3, replacing *W* with *W(FA)*.

Following selection of a FA, the agent selects a patch within that FA. Again, patches are selected based on weighted random choice as in Equation 3, replacing *W* with a different patch selection weight *W(P)*. If the selected FA is the same as the roosting

FA, 3a) then *W(P)* is defined as in Equation 2, replacing *f* and *d* with parameters *f(p)* and *d(p)* that determine how strongly agents weight food density and distance in choosing a patch within a foraging area. If the selected FA is not the same as the roosting FA, 3b) then distance is removed from the weighting to optimize computational effort, as we assume that the relative distances to potential target patches will be relatively similar, given that the individual must first fly to the target FA. In this case,

$$W(P)_{ij} = A_j \times F_j^{f(p)} \qquad \text{(Equ. 4)}$$

When an individual's net foraging intake rate (calorie intake rate - calorie expenditure rate) within a patch falls below zero, the individual abandons foraging in that patch and moves to a new foraging patch. In previous versions, this switch selection was based solely on distance. The agent would move to the next nearest patch with available food and water. In this updated model version, individuals are somewhat smarter, and follow the same within-FA patch selection rule they follow in 3a).

In the case that an individual chooses to switch to a new SB, 2b) the choice of SB again is determined by weighted random choice as in Equation 3, replacing *W* with SB selection weight *W(SB)*. *W(SB)* is again defined as in Equation 2, replacing *f* and *d* with parameters *f(sb)* and *d(sb)* that determine how strongly agents weight food density and distance in choosing a patch within a SB. Once a SB is selected in this level of the hierarchy, patch selection continues as above, selecting a FA as in 2) and a patch as in 3b).

C) Agent parameterization

Table I.1 lists the parameters used in the present model to define the behavior of individual agents and provides notes on sourcing. Landscape parameters are described in Methods II. Details for some specific parameters are described below.

Giving-up density, defined as the food biomass per patch below which agents will no longer select a foraging patch, should ideally be specified per food type; however, the model currently only supports one value per forager type. A weighted mean of published giving-up values per habitat type (woody wetland: 1 g/m^2; herbaceous wetland: 20 g/m^2; corn: 1.5 g/m^2; rice: 5 g/m^2; soybeans: 5 g/m^2) (Gray et al. 2013) was therefore computed based on the proportion of habitat types in the map and applied to all foraging patches.

A mean *attack constant* for mallards, representing search efficiency (m^2/s; *α'* in Holling's disc equation), could not be sourced from the literature except for values derived from experimental settings with unrealistically high food density and/or for peck-feeding, rather than the filter-feeding employed by mallards in wetlands. We therefore used raw experimental data from a study of green-winged teal (*Anas crecca*) filter-feeding on low densities of rice (Arzel et al. 2007), provided by Celine Arzel, to estimate an attack constant appropriate for a filter-feeding dabbling duck in a natural setting.

The *selection weights* for patches, foraging areas, and sub-basins are the parameters *f(fa)*, *d(fa)*, *f(p),* and *d(p)* described in section B that govern how strongly an agent's choice of a destination patch is driven by flight distance vs food density at the various map scales. The *sub-basin switching threshold* is the percentage of maximum lipid storage at which the agent decides to move to another sub-basin because the current one is too low-yield. These values were configured empirically to satisfy model validation requirements (see section D).

The *emigration trigger threshold* is the percentage of maximum lipid storage at which the agent emigrates out of the simulation landscape entirely. The value was based on findings by Whyte and Bolen (1988) that even mallards in relatively poor body condition (~57 g of body fat) were still able to migrate for up to 500 km in response to worsening weather conditions. This metric corresponds to a stored energy value of 513 kcal in the model; thus, the threshold for emigrating out of the simulation due to poor body condition was set to 513 kcal / 3463.1 kcal (empirically estimated maximum lipid reserves) = ~15%.

Earliest and latest daily foraging time ensure that all agents use the same daily schedule and determine the maximum duration of the foraging bout (16 h).

Table I.1. Values, units and sources for parameters determining agent behavior in the Mississippi Alluvial Valley (MAV) mallard model at model initialization.

Parameter	*Initial value*	*Unit*	*Source*	*Comments*
Base metabolic rate	0.00136	kcal/s	Miller and Eadie (2006)	
Metabolic rate multiplier: foraging	2.5		Wooley and Owen (1978)	
Metabolic rate multiplier: flying	12		Miller et al. (2014)	derived by Miller et al. from multiple sources
Metabolic rate multiplier: non-foraging	2		Miller et al. (2014)	weighted mean of several activities
Flying speed	21.4	m/s	Bruderer and Boldt (2008)	
Daily food intake limit	137.5	g	unpublished data	Eadie et al. (UC Davis) in preparation
Maximum lipid reserves	3463.1	kcal	unpublished data	Eadie et al. (UC Davis) in preparation
Starting lipid reserves	1978.9	kcal	unpublished data	Eadie et al. (UC Davis) in preparation
Starting lipid reserves, SD	494.7		unpublished data	Eadie et al. (UC Davis) in preparation
Conversion factor non-lipid <-> lipid	0.537		Miller and Newton (1999)	
Giving-up food density	3.16	g/m^2	(Gray et al. 2013)	area-weighted mean of values for individual habitat types
Maximum forager density per patch	1	$1/m^2$	Miller et al. (2014)	field observations
Earliest daily foraging time	17:30		Miller et al. (2014), unpublished data	composite of estimate derived by Miller et al. from several sources, and K. Ringelman (pers. com.)
Latest daily foraging time	09:30		Miller et al. (2014), unpublished data	composite of estimate derived by Miller et al. from several sources, and K. Ringelman (pers. com.)
Attack constant	0.00127	m^2/s	unpublished data	calculated from the raw experimental data (unpublished) used in Arzel et al. (2007)
Handling time	2	s	Miller et al. (2014)	derived by Miller et al. from multiple sources
Patch selection weights distance : food density [*d(p) : f(p)*]	1 : 3		empirical estimation from simulation tests	configured to satisfy model validation requirements (see section D)
Foraging area selection weights distance : food density [*d(fa) : f(fa)*]	1 : 3		empirical estimation from simulation tests	configured to satisfy model validation requirements (see section D)
Sub-basin selection weights distance : food density [*d(sb) : f(sb)*]	0.5 : 3		empirical estimation from simulation tests	configured to satisfy model validation requirements (see section D)
Sub-basin switching threshold	50%		empirical estimation from simulation tests	configured to satisfy model validation requirements (see section D)
Emigration trigger threshold	15%		Whyte and Bolen (1988)	estimated from reported lipid stores

D) Model validation

In developing the model for application to the MAV, we set several targets for realistic behavior and outcomes that were used to validate the model. These consisted of targets that were partly identical to the validation targets set for the previous model version in Miller et al. (2014) and partly of targets more specific to the present model and the region under simulation.

All results reported below were derived from 136 replicate runs of 120 days each. These runs used agent parameterization as described above (section C) and the base map under standard (average) inundation conditions with probabilistic patch flooding, as described in Methods II. Data series shown were left-truncated on day 30 (November 30) to remove the period during which dynamics may be obscured by daily addition of large numbers of agents immigrating into the landscape (see Methods III A). Criteria are discussed in order of increasing specificity to the MAV model.

- Mallards disperse to foraging patches

Agents in the simulation are expected to disperse to foraging patches across the map in dynamic response to changes in food availability and foraging efficiency. This behavior can be tracked through the median proportion of foraging time spent in different habitat types. A comparison of this metric for the model's five principal foraging patch variants (herbaceous and woody wetlands, soybeans, rice, and corn) shows the expected pattern of seasonal dynamics, corresponding to agent relocation across the map in response to changes in food energy distribution (Fig. I.3–I.7). The shaded areas (range band) represent bilateral 95% value ranges.

Figure I.3

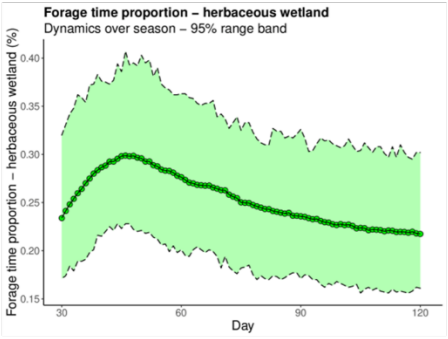


Figure I.4

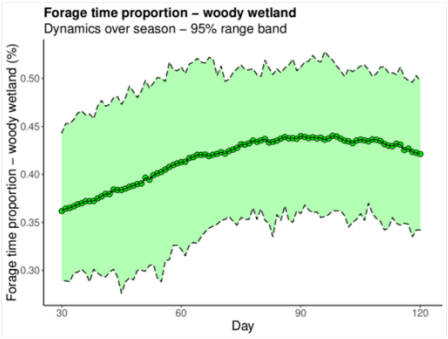


Figure I.5

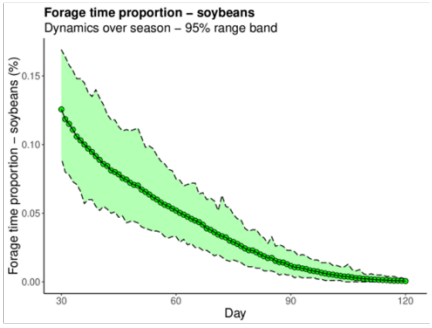


Figure I.6

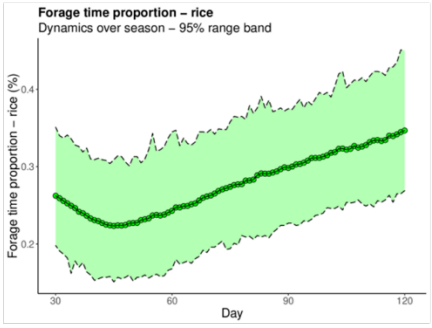
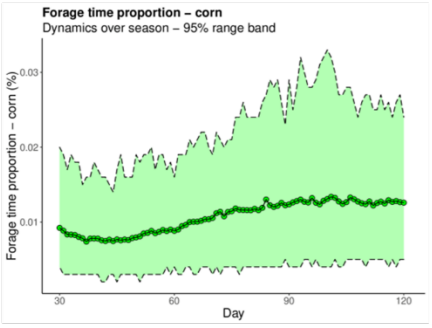


Figure I.7



● Food resources are depleted from patches throughout the season

Food biomass is assumed to have been produced in the months preceding winter and then depleted by both natural decay and agent foraging over the course of the simulation. The development of summed food energy in the flooded (i.e., available for foraging) part of the landscape shows that the expected steady decrease over the season was present (Fig. I.8). The shaded areas (range band) represent bilateral 95% value ranges.

Figure I.8

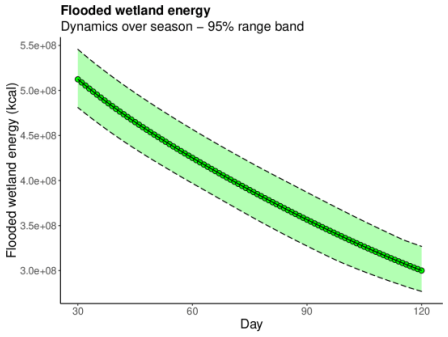
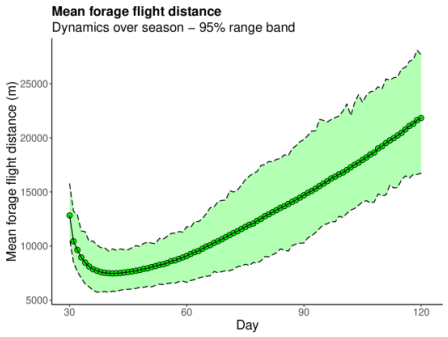


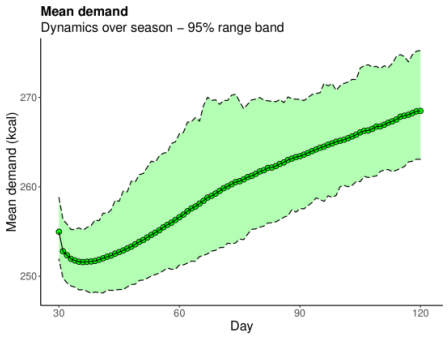
Figure I.9



● Metabolic cost progresses with the season

As winter progresses and food resources are depleted, mallards are expected to incur greater energy costs due to increasing flight distances among diminishing food supplies, and greater frequency of relocation movements due to localized depletion. As expected, mean foraging flight distances increased throughout the season (after an initial period of settling into optimal early exploitation locations; Fig I.9), and mean demand (representing energy expenditure that has to be satisfied by acquiring food energy) subsequently increased (Fig. I.10). The shaded areas (range band) represent bilateral 95% value ranges.

Figure I.10



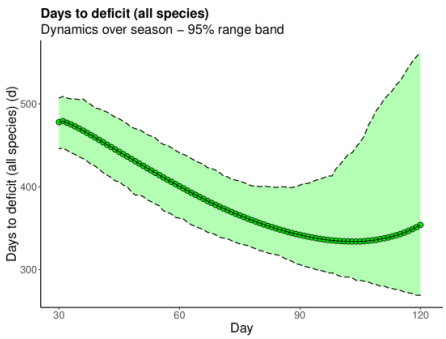
● Daily energy requirements are within the range observed from empirical data

The estimated daily energy requirement of a “generalized dabbling duck” is 294.5 kcal/day (Gray et al. 2013); Miller et al. (2014) used a target range of 225-280 kcal/day for a combination of waterfowl species. Because mallard body mass tends to be toward the upper end of the range of body mass for dabbling ducks, we thus set a target range of 240-295 kcal/day. Observing the dynamics of mean energy demand over the season (Fig. I.10) shows median values of 255-270 kcal/day, with a bilateral 95% value range interval of 245-285 kcal/day, placing this metric well within the expected range.

● Days to deficit at largest population size exceeds the length of the remaining season

Days to deficit refers to the number of days until the average forager could no longer meet the current daily energy requirements, given current available landscape food energy. The modeled landscape is expected to provide at minimum sufficient energy to sustain the simulated population for the duration of the modeled season. Days to deficit alters over the course of the season as both landscape energy and the demands on foraging behavior change, and is thus of limited use as a forecasting metric; for greatest utility, it is best evaluated at the time of maximum population size. In the present model, this point is just after immigration into the region has halted (day 30). Results show that the median metric is well in excess (490 days) of the required threshold of 90 days at that time, and remains above it throughout the season (Fig. I.11). The shaded areas (range band) represent bilateral 95% value ranges.

Figure I.11



● Distribution of flight distances conforms to observations from empirical data

Beatty et al. (2014) used location records of satellite-tracked mallard hens to investigate habitat selection in the MAV at different spatial scales. They derived a frequency distribution of mallard movements over different distances that shows a distinct peak in the frequency of movements between ~250 m and 30 km (interpreted as local relocations during foraging), and a much reduced frequency for longer movements (interpreted as long-distance relocations). This distribution provides a useful summary of the expected movement patterns of mallards in the region. We therefore set a validation target of approximating this empirical movement distribution in the simulation outcomes. During map development for the present model, we took the availability of these data into account when selecting the area to be represented in the simulation, and selected a map location that contained a high number of location records from the evaluated set (see Methods III).

After the basic configuration of map and agent parameters were established sufficiently to constrain the model from generating unrealistic population losses (e.g., rapid emigration of the majority of mallards under good forage conditions), parameters were not further adapted to achieve a population target. Rather, parameter tuning was then used to meet the target distribution of flight distances. The energetics of agents and ultimately, the rate of population decline under standard conditions, is therefore a consequence of the parameterization as driven by the flight distances distribution. Because actual winter emigration rates of mallards from the MAV are unknown, we regarded this method of deriving emigration rates as an emergent property as the most appropriate approach.

The model parameters adapted to approximate the distribution were the number and placement of refuge sites used for roosting (for more details on refuges see Methods III); number of foraging areas and sub-basins in the landscape; and the distance-vs-food decision weights for switching between patches, foraging areas, and sub-basins [*f()* and *d()*]. The latter two factors are important

in driving hierarchical patch selection - see section I B for details. Because there exists essentially no field information about these factors, we considered it suitable to use them for tuning model behavior.

We conducted iterative tests of parameter values and made qualitative evaluations of their effect on the target distance distribution. We found that the best approximation could be achieved with the following combination:

- The map was partitioned into **15 SBs**, each of which contained **107 FAs**, each of which contained a mean of **100 patches** (with a wide variance). This landscape has a few large sub-basins, between which there was infrequent long-distance movement, and a large number of foraging areas, which made up the majority of mid-range movement targets when agents relocated between them and the relatively sparse roosting sites.
- The map contained five randomly placed refuges (locations available for roosting) per sub-basin, plus twice as many randomly distributed within sanctuary areas (75 + 150 = **225 refuges**). This relatively small number of roost patches for agents to choose from stimulated the expected proportion of mid-range relocations at the end and beginning of each foraging bout. Refuges were placed at a greater density in sanctuaries because it was assumed that absence of hunting and other disturbances would increase the attractiveness of these areas as roosting locations (note that explicit disturbance/hunting is not implemented in the present model).
- The weight ratios of movement distance : food density that agents use to choose a target patch for relocation were set to **1 : 3** for choosing a **patch** within a FA [*d(p)* = 1, *f(p)* = 3]; **1 : 3** for choosing a **FA** within a SB [*d(fa)* = 1, *f(fa)* = 3]; and **0.5 : 3** for choosing a **SB** [*d(sb)* = 0.5, *f(sb)* = 3]. Thus, at all levels of the hierarchical choice process, the most realistic results were achieved by assuming that the food density at the target location was of greater importance than the required flight distance, and this weighting was most pronounced for the longest relocations (between sub-basins).

To derive flight distances for this comparison, movement records for all agents were extracted from the model at 6 h intervals, which corresponded to the reporting frequency of the empirical movement data in Beatty et al. (2014). One major characteristic of the empirical distribution that cannot be matched by the simulation is the high frequency of movements at short distances (below ~100 m). The model does not feature such movements because agents only move between but not within patches; that is, they do not perform the frequent small relocations that a duck would carry out while foraging within a patch. Small movements do occur if agents switch to neighboring patches and are positioned close to the shared border before, as well as after, the switch, but these instances are rare. Instead, the model reports a large number of zero distance moves because agents remain stationary within a patch most of the time; this again is not present in real observations. We thus excised the zero distances from the output and expected the model to conform to the observed distribution at longer movement distances only.

Figure I.12 shows a comparison of the distance frequency distribution derived from the tuned simulation and empirical distribution on a logarithmic scale. The expected drop-off in frequency around the 30-km range is present, although it is more gradual in the simulation. There is a marked peak in mid-distance movements >5–15 km, indicating that this was the most common distance range between refuges and foraging patches, representing an effect of the limited number of available refuges. The lack of simulated short-range movements is visible and yields a more left-skewed distribution. Consequently, the model overall featured larger median movement distances than the field data (5.5 km vs 3.1 km). However, given the above caveats and

the simplified representation of daily foraging behavior in the model, the two distributions were considered sufficiently similar (overlap 66%) to indicate that agents in the model displayed suitably realistic foraging behavior.



Figure I.12. Comparison of frequency distribution of mallard movement distances from field observations (black line; Beatty et al. 2014) and simulation (green line; based on 240 replicate runs of 120 days), on a log10-transformed distance scale.

E) Model assumptions

The model includes many simplifications and assumptions about mallard behavior and physiology, landscape and environmental dynamics, and conservation management effects. The majority of these are discussed in context in Methods sections I-III. The following is a list of model assumptions that are not covered elsewhere.

- The model covers the wintering season only and does not include seasonal changes in mallard behavior and physiology (such as changes in food preference and accelerated build-up of lipid reserves close to spring migration).
- Mallard mortality from sources other than hunting (not represented in the model) is minimal or absent in the MAV during the wintering period (Reinecke, Shaiffer, and Delnicki 1987; Dugger, Reinecke, and Fredrickson 1994; Link 2007). Mortality can therefore be disregarded as a factor affecting the number of mallards leaving the simulation, and the model focuses on emigration as the sole exit mechanism.
- Mallards feed only in flooded foraging habitat. This is untrue (Jorde, Krapu, and Crawford 1983; Calicutt, Hagy, and Schummer 2011), but this simplification was adopted because the majority of wintering mallard foraging in the MAV occurs in wetlands or flooded fields (Edwards et al. 2012; Herbert et al. 2021), and because the flooding status of foraging patches provided the best available mechanism for simulating different environmental conditions.
- All wetlands have water management capability.

- At the time point represented by a given scenario, newly established easement wetlands (restored or natural) have similar water and food biomass production capability as existing easements.
- The inundation status of each foraging patch does not change over the course of the winter season unless specifically manipulated.

II) Map preparation and parameterization

A) Scale

The model was developed to represent foraging behavior during the wintering period. Map scale was chosen to enable adequate simulation of this behavior. During wintering, mallards make use of foraging habitat mostly within a radius of ~30 km around a refuge (Beatty et al. 2014), suggesting a minimum simulation scale of ~60 × 60 km (assuming a central refuge), as used in Beatty et al. (2017).

However, a somewhat larger scale was required to allow mallards to move among multiple refuges. Further, the use of scenarios employing geospatial data suggested the choice of a scale unit with some connection to local landscape configuration. We therefore considered the different classes of USGS hydrologic units (HUCs; USGS 2013), which are determined by watershed configurations at multiple scales. These offered the benefit of placing unit boundaries at maximum distance from bodies of water at a given scale, thus increasing the likelihood of not artificially bisecting functional foraging habitat units. We selected the 6-digit HUC (HUC6; Basin) as the most suitable unit area. With a mean area of 27,000 km^2, it is 7.5 times the size of the simulation area used in Beatty et al. (2017; 3,600 km^2). The next smaller unit (HUC8) would be too small, at only half maximum foraging range (1,800 km^2; Table II.1).

A rough estimate of the number of agents requiring simulation at this scale for locations in the Mississippi Flyway was derived from the USFWS Mid-Winter Waterfowl Survey (USFWS 2016). Total mallard numbers across the entire survey period were summed across all years for each reporting unit in the flyway, then the grand mean was divided by the approximate number of HUC6 units per reporting unit. The mean of HUC6-level maximum number of mallards reported was 125,000, suggesting a general requirement for simulating more than 10^5 but less than 10^6 birds (Table II.1).

Table II.1. Types, size, and number of USGS hydrologic units (HUC units) in the continental United States (CONUS), and approximate mean number of mallards / HUC estimated in U.S. Fish and Wildlife Survey (USFWS) Mid-Winter Surveys for units of that size. Mean of maximum: mean of annual maximum abundances across all years.

				Mallard density	***Mallard density***
HUC unit	***Type***	***Number (CONUS)***	***Mean size (km^2)***	***Overall mean***	***Mean of maximum***
2-digit	Region	21	460,000	480,000	2,050,000
4-digit	Subregion	222	44,000	46,000	200,000
6-digit	Basin	370	27,000	29,000	125,000
8-digit	Subbasin	2270	1,800	2,000	9,000
10-digit	Watershed	20000	590	600	3,000
12-digit	Subwatershed	100000	100	100	400

B) Selection of location

Choice of location was based on several considerations. First, the candidate area was narrowed to the region of the Mississippi Flyway that showed consistent presence of wintering mallards, based on data from the USFWS Midwinter Waterfowl Survey (MWS; USFWS 2016). Survey subsections were removed if population numbers were below median numbers for the complete section for the period 1981-2016 (subsections were not consistently in use prior to 1981), with boundaries approximated by the closest HUC6 boundary.

Next, four location criteria were evaluated:

Habitat representativeness: The main criterion. The area should have a similar distribution of habitat types as the total area of interest, to ensure broad applicability of findings correlated to habitat distribution. Similarity was assessed based on the four National Land Cover database (NLCD) categories that describe potential mallard habitat: woody wetlands, emergent herbaceous wetlands, crops (collectively), and open water (Yang et al. 2018).

Easement distribution: Scenarios featuring different numbers and characteristics of easements represented the main model use case, and it was important that the map location was within the continuum of easement distribution across the MAV. However, easement distribution cannot be expected to be directly correlated to habitat representativeness. We therefore divided all candidate locations into classes (inter-quartile ranges) by total amount of easement area; identified the best candidate within each range; and selected from the first range (top 25% of locations by easement area) for the initial model. We included the following easement types, obtained from the National Conservation Easement database (NCED 2018): WRE/WRP; Emergency Wetland Reserves; and Floodplain Reserves.

Substantial populations: Model results are of greater interest if they pertain to areas with high wintering mallard populations. The map region should thus preferably be located in such an area.

Verifiability: The validation of model predictions using existing field data was desirable. A database of tracked locations of mallards wintering in the flyway was available for this purpose (Beatty et al. 2014; Kesler et al. 2014). A location containing a high number of tracking records was therefore preferable.

It was impractical to restrict screened locations to actual HUC6 units, as these generally have highly irregular shapes that would be problematic to model (in particular, elongated sections following stream watersheds would force agents into unrealistic movement corridors). To retain future compatibility with locations where actual HUC6 units could be employed, we instead delineated candidate locations for screening as circular areas of the desired size (27,000 km^2). The circular boundary of selected candidate areas was then replaced with an approximation of boundaries at a higher HUC level (HUC10 – "watershed" size), which retains the quality of boundaries being placed away from bodies of water. This on average increased location areas by ~5%.

Candidates were screened using a "moving window" type approach in ArcGIS Desktop 10.6.1 (ESRI 2018). The reduced flyway area was covered with a raster of circles of the desired area, spaced at 0.5 × circle radius (46.6 km). This ensured that the majority of points on the map were covered by 16 different circles, and ~95% were covered by at least four circles. Circles with an area below 20,000 km^2 (~75% HUC6 area) were discarded to reduce boundary effects, resulting in 249 overlapping candidate areas (Figure II.1). For each candidate area, we calculated the proportion covered by each of the four habitat categories, and the proportion covered by easements. Similarity in habitat distribution between each candidate and the total area was tested using a chi-square test. Candidate areas were ranked by increasing chi-square statistic (i.e., decreasing model fit, or decreasing similarity). The ranked list was then divided into four inter-quartile ranges by decreasing area covered by easements (greatest coverage in first range).

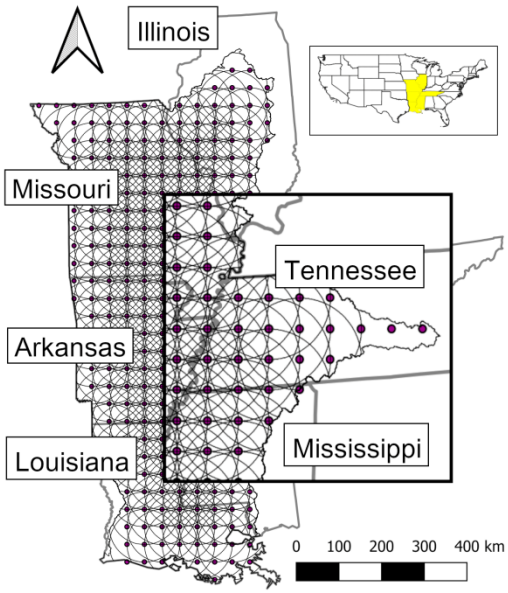


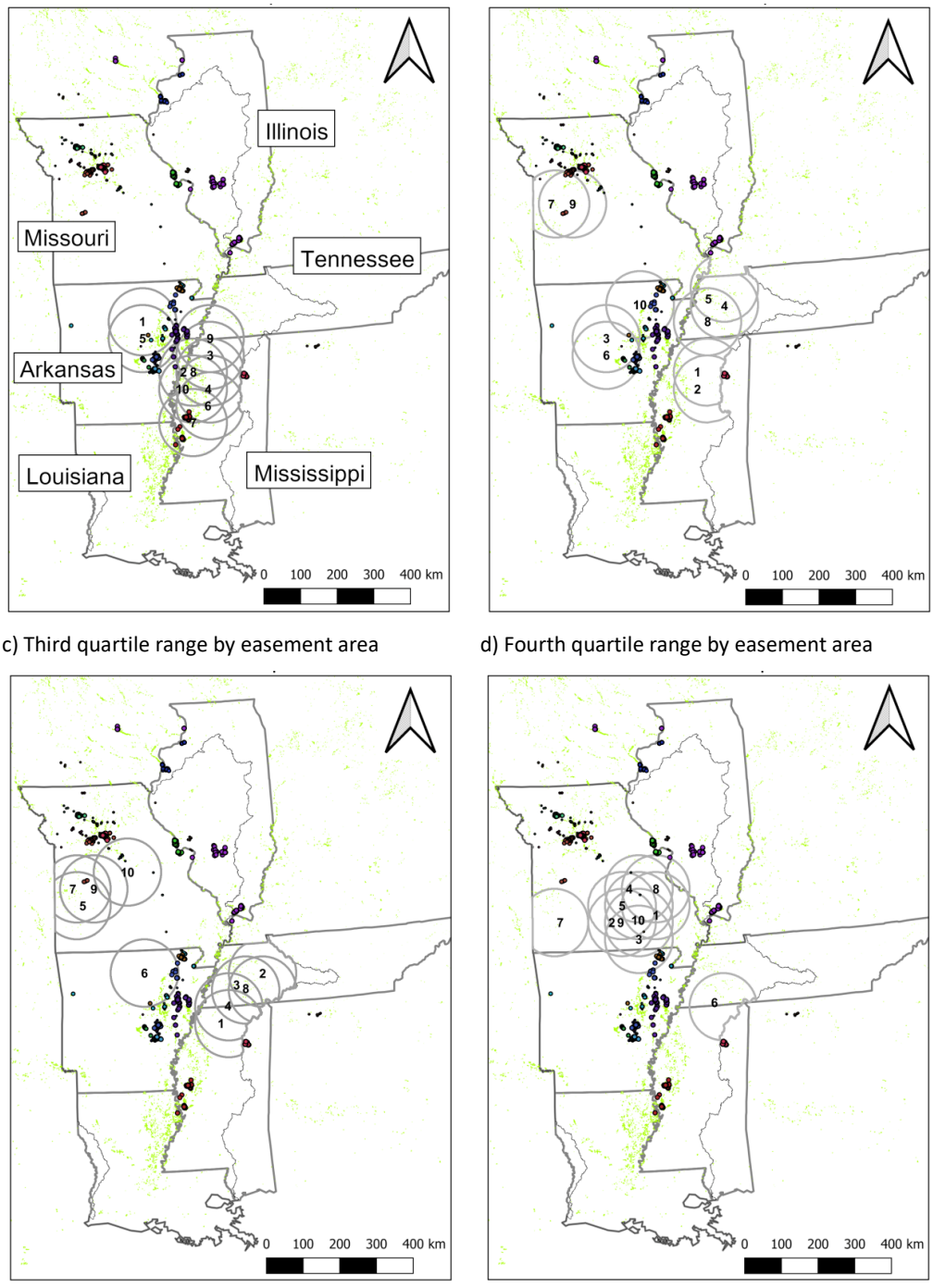
Fig. II.1. Core Mississippi Flyway area with midpoints and radii of circles of mean hydrologic unit (HUC) HUC6 area (27,000 km^2) on a 0.5 × circle radius grid. Circles of <~75% mean HUC6 area were removed. Top inset shows position within continental United States, lower inset shows enlarged view of an example section (Tennessee). State lines are shown in grey.

We identified the ten candidate locations that exhibited the greatest habitat similarity to the entire region, ranked by covered easement area (in four quartile ranges; Figure II.2). All top candidate locations in the first range clustered around the main channel of the Mississippi River, whereas candidates in lower ranges occurred increasingly away from this region. We found that

habitat similarity was greatest among candidates with the greatest proportion of easement area (first range). This reinforced the decision to choose the location for the wintering model with reference to high easement area proportion, and indicated that it should be selected close to the Mississippi River channel. Almost all good candidates with these characteristics were located in either Arkansas or Mississippi.

a) First quartile range by easement area

b) Second quartile range by easement area



c) Third quartile range by easement area

d) Fourth quartile range by easement area

Figure II.2. The 10 candidate areas (circles) most similar by habitat distribution to the total area (grey state lines), ranked by covered easement area (e.g., first quartile range contains top 25% of candidates by easement area). Easements are shown in green. Dots indicate locations of mallard tracking records available for model validation, colored by individual and sized proportional to number of records per individual. State names are shown in 1st quartile image (top left).

Among the candidates in the first easement coverage range, an Arkansas location was preferable to a Mississippi location because wintering mallard abundance since 1955 has been consistently greater in Arkansas (median: 784,000) than in Mississippi (median: 219,000; USFWS 2016). Additionally, there were substantially more tracking records of individual mallards available in Arkansas than in Mississippi (Figure II.2). We therefore selected an Arkansas location in quartile range that covered a large number of tracking records. Figure II.3 shows the chosen location as original circular area and as approximated by HUC10 boundaries. It is located in east-central Arkansas, with center point at 91° 26’ N, 34° 40’ E.



Figure II.3. Location of selected simulation area for the Mississippi Alluvial Valley (MAV) mallard model, in east-central Arkansas. Circle (red): area used for selection, with midpoint at 91° 26’ N, 34° 40’ E, size 27,000 km^2. Outline (black): area approximated using hydrologic unit (HUC) HUC10 boundaries, size 29,353 km^2. State lines are shown in grey.

C) GIS map development

Data sources

All GIS processing was conducted using ArcGIS Desktop 10.6.1. and QGIS 3.0 or more recent versions. The following GIS geospatial data sources were used to develop the map:

Cropland Data Layer (release 2019, CDL; USDA 2018) – Raster, 30 × 30 m. This data layer was used as the main source for map content and baseline for habitat type identification and location. It is based on the same underlying data as the latest release of the NLCD dataset (Yang et al. 2018), but in addition includes distinctions among agricultural crop types.

National Wetlands Inventory (version October 2019, NWI; USFWS 2019) – Polygon. This dataset was originally considered as a source for fine distinctions among wetland types by vegetation community. However, we decided against making extensive use of this data layer because much of the data were outdated, especially relative to restored wetlands. For the MAV in particular,

including the selected map location, the majority of data were based on surveys from the 1980s or earlier; the quality of information about the extent of wetlands (especially herbaceous types) in this region is uncertain. We thus limited our use of NWI data in creating the basic simulation map to determining the extent of woody wetlands within the current extent as provided by CDL that was not classified as "broad-leaved deciduous", and removed this from foraging patches (see below). We did however make use of NWI records in developing a specific group of scenario maps ("increasing easement area using NWI patches only" – see Methods III).

Southeast Floodplain Inundation Frequency (Allen 2016) – Raster, 30 × 30 m. This dataset provides estimates of mean annual inundation frequency (i.e., probability of flooding in any given year) across the MAV for the period 1983–2011. It is based on Landsat and other imagery, using material from December–March only, which makes estimates more reliable for vegetated wetlands than similar available datasets, due to the general absence of obscuring foliage.

National Conservation Easement Database (release 2018, NCED; NCED 2018) – Polygon. This dataset provides the geographical outlines of conservation areas and their classification by program, holder and landowner type, establishment date, and some notes on habitat composition and management. It was used to identify habitat patches as belonging to a specific easement and easement type, and reclassify some contained habitats based on assumed restoration activities (see below). The following separate groupings were observed for future scenario manipulations: WRE/WRP/EWR/FR (collectively, "easements"); Ducks Unlimited; and public lands.

Three additional datasets were used that are not publicly available. Records for the easement types of interest queried from the National Easement Staging Tool (NEST; last updated 2017) were kindly provided by David Williams (NRCS, Fort Collins, CO) following a request by Greg Pipkin (NRCS, Fort Collins, CO) and Charles Rewa (NRCS, Washington DC). These records were used to parameterize management status and specific habitat restoration measures in easements.

Records for public land parcels from the Public Lands Water Management Unit Inventory, maintained by the Lower Mississippi Valley Joint Venture (LMVJV; winter 2013-2014), were kindly provided by Blaine Elliott (LMVJV). These records were used to determine percent red oak (*Quercus* spp.) of woody wetlands and harvest of crops on public lands, and modify CDL-based habitat types following land usage notes.

Records for National Wildlife Refuge areas, and for areas owned and/or managed by state agencies, that were designated as unhunted waterfowl sanctuaries were compiled from separate sources by Beatty et al. (2014). These records were used to assign sanctuary status to specific areas, which partly governed distribution of roosting locations (see Methods I).

Resolution and partitioning

The spatial resolution of the map was dictated by that of the main underlying data source (CDL; 30 × 30 m). SWAMP uses vector-based maps, and all raster data sources were transformed to vector format during processing. The transformation preserved the exact outline of raster pixels ("blocky" borders), allowing 1:1 transference of attributes by area. The smooth polygon outlines of conservation areas as provided by NCED were adapted to this resolution by rasterizing (using a majority-by-area rule for attribute determination), then re-polygonizing to raster outlines.

Map data in SWAMP are processed in the form of **patches**. A patch consists of a single contiguous habitat polygon marked as belonging to a single habitat variant as determined from the underlying GIS data. Each patch type was characterized by a specific combination of parameters that governs how agents interact with that patch type, and separately defined. For example, all patches of woody wetland with 20% red oak coverage have one common patch type. Map features that do not have an assigned patch type are considered to have no interactions with agents and thus have no function in the simulation process; while these map data have been retained to preserve information on landscape composition and configuration, they were excised from the map layer used to govern agent movement. When agents travel to a patch (to rest or forage), they determine the closest point in the patch as target. If this position is within exclusion distance of another forager, location within the patch is randomized.

This framework imposed two contradictory requirements on map preparation. On the one hand, fine patch partitioning was desirable because the random placement of incoming agents within a contiguous target patch meant that if the patch was very large, the agent might be forced to travel an unreasonably long distance to relocate. We addressed this issue by further subdividing the large contiguous patches that occurred among the crop and woody wetland habitats. Patches were automatically subdivided into polygons with maximally 72 vertices, resulting in subsections of random size but on average comparable to the size of an average easement. These alterations were not applied to patches on conservation land, to allow future analyses of the effect of varying easement size.

On the other hand, map complexity had to remain limited for reasons of simulation efficiency. The conversion of raster data to polygons at high resolution, and subdivision of otherwise contiguous habitat patches by other parameters (principally inundation frequency), produced a very large number of distinct patches (~10^6). While SWAMP is capable of processing maps of this complexity, the cost in simulation speed and memory resources would have made effective analysis of scenarios impractical at high replication. We therefore imposed simplifications and broad categorizations on the available habitat data at the expense of data resolution (see below), and employed various procedural map simplification steps. The number of polygons was reduced to ~1.5×10^5 (reduction by 85%), which allowed simulation at an acceptable speed. Polygon reduction consisted of applying a "majority-by-area" filter to areas highly fractionated by inundation overlay (growing common local inundation levels at the expense of less common ones), and of merging isolated 1- or 2-pixel patches into larger neighboring patches or the empty background. Figure II.4 shows an example of a map section before and after applying these steps.

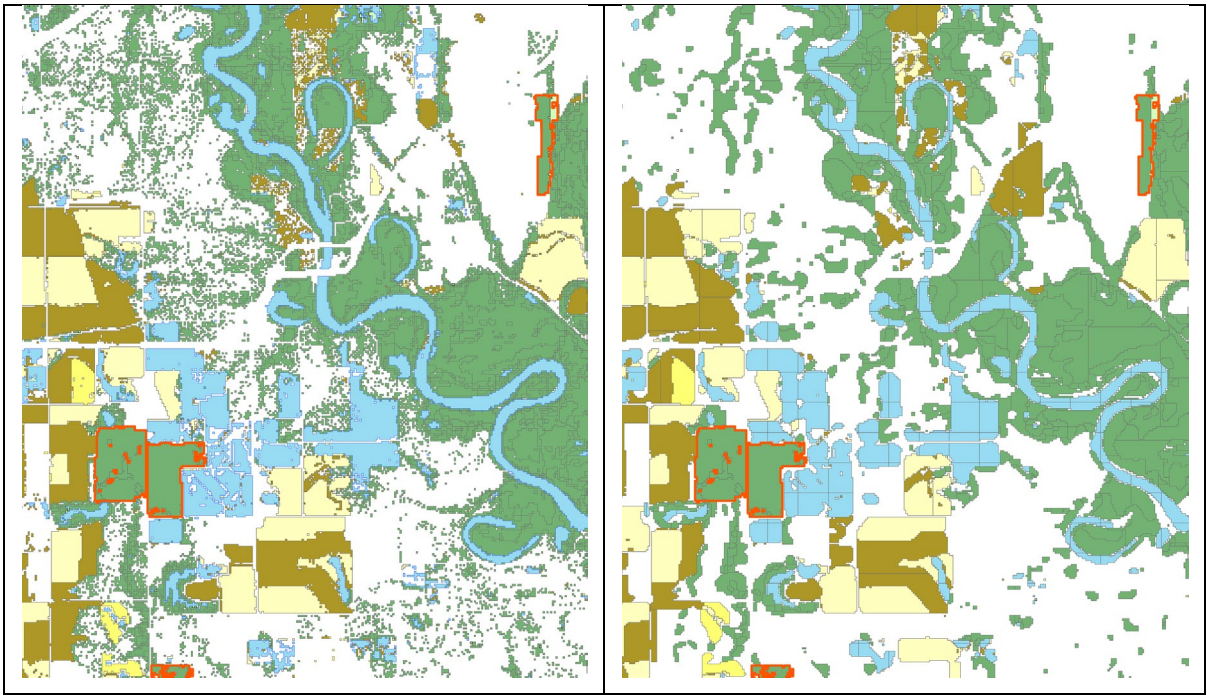


Figure II.4. Comparison of a map section of the simulation map for the Mississippi Alluvial Valley (MAV) mallard model, before (left) and after (right) applying polygon reduction and large contiguous area subdivision. Small isolated polygons were merged or removed, and large contiguous areas outside of conservation land were partitioned by irregular grids. (Note that open water areas have also been partitioned; this has no bearing on model outcomes, as use of open water as potential roosting areas was removed later in model development.)

D) Map parameterization

Foraging habitat types

Parameterized foraging habitat comprised 33.2% (9,732 km^2) of the total map area (29,353 km^2; Figure II.5). It consisted of five principal land cover categories: woody wetlands, herbaceous wetlands, corn, rice, and soybeans. All of these categories are considered foraging habitats that mallards evaluate and visit based on their food availability and energy content. Open water is shown on scenario maps as a visual aid for the presence of river channels and bodies of water, but has no functional interaction with mallards in the simulation. Wetland classification as implemented in the CDL and NWI datasets follows the categories published by the Federal Geographic Data Committee (FGDC 2013), but categories were further combined and simplified for map use.

Woody wetland represented broad-leaved deciduous forested wetland with at least some amount of red oak species (*Quercus* spp.; including *Q. palustris*, *Q. phellos*, *Q. nigra*, and *Q. texana*; Kaminski et al. 2003), the acorns of which make up the main food source for dabbling ducks in this habitat (Gray et al. 2013). The NLCD/CDL category of this name also includes a number of related habitat types, such as evergreen and shrub/scrub wetlands, that have minimal energetic value to foraging ducks and should thus not be modeled as potential foraging targets (Gray et al. 2013). Comparison with NWI coverage suggested that these low-energy (non-red oak) habitats made up ~17.5% of all woody wetland, which was considered too large a percentage to ignore. We therefore excised the NWI-delineated areas of low-energy habitats from the CDL data before further processing. The resulting habitat type made up 50.9% of map habitat and 82.5% of easements.

Herbaceous wetland represented wetland habitat containing non-woody vegetation. The NLCD/CDL category of this name includes both persistent and non-persistent vegetation types as well as wetlands dominated by invasive *Phragmites* grasses. Parameterization from the literature is primarily available for moist-soil (seasonally flooded herbaceous) habitats only, which make up the majority of the non-persistent wetland category. However, comparison with NWI coverage indicated that the other two types are sufficiently rare in the area of interest (<0.5% of herbaceous wetlands) to not require removal. In the following, this habitat was treated as representing moist-soil habitat *sensu* Gray et al. (2013). It made up 1.7% of map habitat and 17.4% of easements.

Soybeans, rice, and corn represented fields of sown agricultural crops that are browsed for waste grain by wintering ducks, generally post-harvest and when flooded. In combination they made up just under half of the available foraging area (47.4%; 25.6%, 20.2%, and 1.6% respectively for soybeans, rice, and corn). A small amount of these three crops was present on public land (making up 0.9% of total conservation land) but not in easements. Other crops were only present in the selected location in negligible amounts (<0.1%) and were removed. Records indicate a small number of crop patches on public land that at times might be left either unharvested or partly harvested for the benefit of foraging birds (B. Elliott, Lower Mississippi Valley Joint Venture[1] unpublished data). However, these patches were removed from the simulation because their much greater food biomass (up to several hundred times larger than harvested fields) had a disproportionate effect on mallard behavior, drawing in much of the total population and swamping more subtle map characteristics. This was considered too large an effect to base on the uncertain data available about the actual status of these fields. Consequently, all crops were treated as being completely harvested at the start of simulation.

Flooding

Flooding frequency determined the probability that any patch of this type will be marked as **flooded** when inundation occurred. Flooded status determined whether a specific patch was available as foraging habitat; it was assumed that no wetland or crop patch could be foraged if it was not flooded. Flooding was determined for each patch separately using its flooding probability. In all scenarios except the active flooding scenarios, inundation happens at the start of the simulation (day 1) and remains in effect for the full simulated period of 120 days. In active flooding scenarios, partial area flooding may happen later in the season (see Methods III). Under standard conditions, ~37% of the map was flooded on average.

Flooding frequencies were combined into five classes (0-2% [0%], 3-25% [25%], 26-50% [50%], 51-75% [75%], 76-100% [100%]) and overlaid on crop and wetland patches. If these patches were located on conservation land, a majority inundation value was determined for otherwise contiguous patches and assigned to the entire patch, as flooding here was expected to be managed to some extent and affect entire areas considered as management units. Outside of conservation land, inundation levels were allowed to further subdivide contiguous areas, as unmanaged flooding here may drive the functional delineation of patches.

[1] At the time of publication, data were not available from the Lower Mississippi Valley Joint Venture

Due to reported limitations of the image-analysis process used to develop the inundation data layer (Allen 2016), a larger than expected number of habitat patches appeared in the 0-2% bracket. Because all habitats classified as wetlands were considered to be able to experience at least rare flooding, wetlands in this category were retained in the map, and treated as floodable only under high-flooding probability environmental conditions. Under these circumstances, they were upgraded to a flooding probability class of 25%. All managed or restored wetlands (see below) in this bracket were also upgraded to the 25% class because it was assumed that active management ensured at least intermittent flooding. In contrast, all crop patches in this bracket were removed from the map, as it was not possible to distinguish between never-flooded fields (which clearly exist) and misclassified fields. The retained non-flooding wetland patches make up ~25% of the total forageable area and consist almost entirely of woody wetland (99%), principally along the course of the Mississippi.

Management status

Management status was a modifier of woody and herbaceous wetland patches and one of multiple components that determined food biomass/energy values (see below). By default, all wetlands outside of conservation land were considered 'unmanaged'. Within easements, management status was assigned based on available information, with 'unmanaged' assumed if no information to the contrary was present in the databases.

For woody wetland, 'managed' and 'unmanaged' was connected to red oak percentage, which in turn drives food biomass for dabbling ducks. Red oak percentage is the proportion of red oak species present in a type of woody wetland patch. Food biomass and energy content values corresponding to percentage levels were obtained from Gray et al. (2013). Specific values for individual patches were only available for public land (B. Elliott, Lower Mississippi Valley Joint Venture[2] unpublished data). The mean of these patches was taken as an estimate for percent red oak in managed woody wetland where this information was missing. While a range of values was given for the public land parcels, all values were combined into three levels to reduce patch type number: 20%, 40%, and 70% ("oak-rich woody wetlands"). These categories provided increasing amounts of food biomass, with minor differences in energy content per gram (see next section). The categories respectively made up ~97%, ~3%, and <0.1% of woody wetlands in the available foraging habitat. Unmanaged woody wetlands were treated as belonging to the 20% red oak percentage category due to absence of management for mast trees (Lower Mississippi Valley Joint Venture 2015); whereas managed woody wetlands were classified as the 40% category (which was approximately the mean of public land red oak percentages; B. Elliott, Lower Mississppi Valley Joint Venture2 unpublished data).

For herbaceous wetland, 'unmanaged'/'managed'/'restored' similarly translate into different food biomass with minor differences in food energy content (see next section). Absent information to the contrary, the default status of herbaceous wetland was set to unmanaged. Managed status was assigned if this information was indicated in the databases. Restored herbaceous wetland status was applied to patches that were considered to have been created from another patch type by active management: A) where NEST data recorded cropland restoration to herbaceous wetland; B) where any type of crop or fallow

[2] At the time of publication, data were not available from the Lower Mississippi Valley Joint Venture

cropland was present inside an easement area during base map creation; and C) where crop patches were added to new easements in area increase scenarios (see Methods III). On the base map, these three categories made up ~18%, ~24%, and ~58% of herbaceous wetlands.

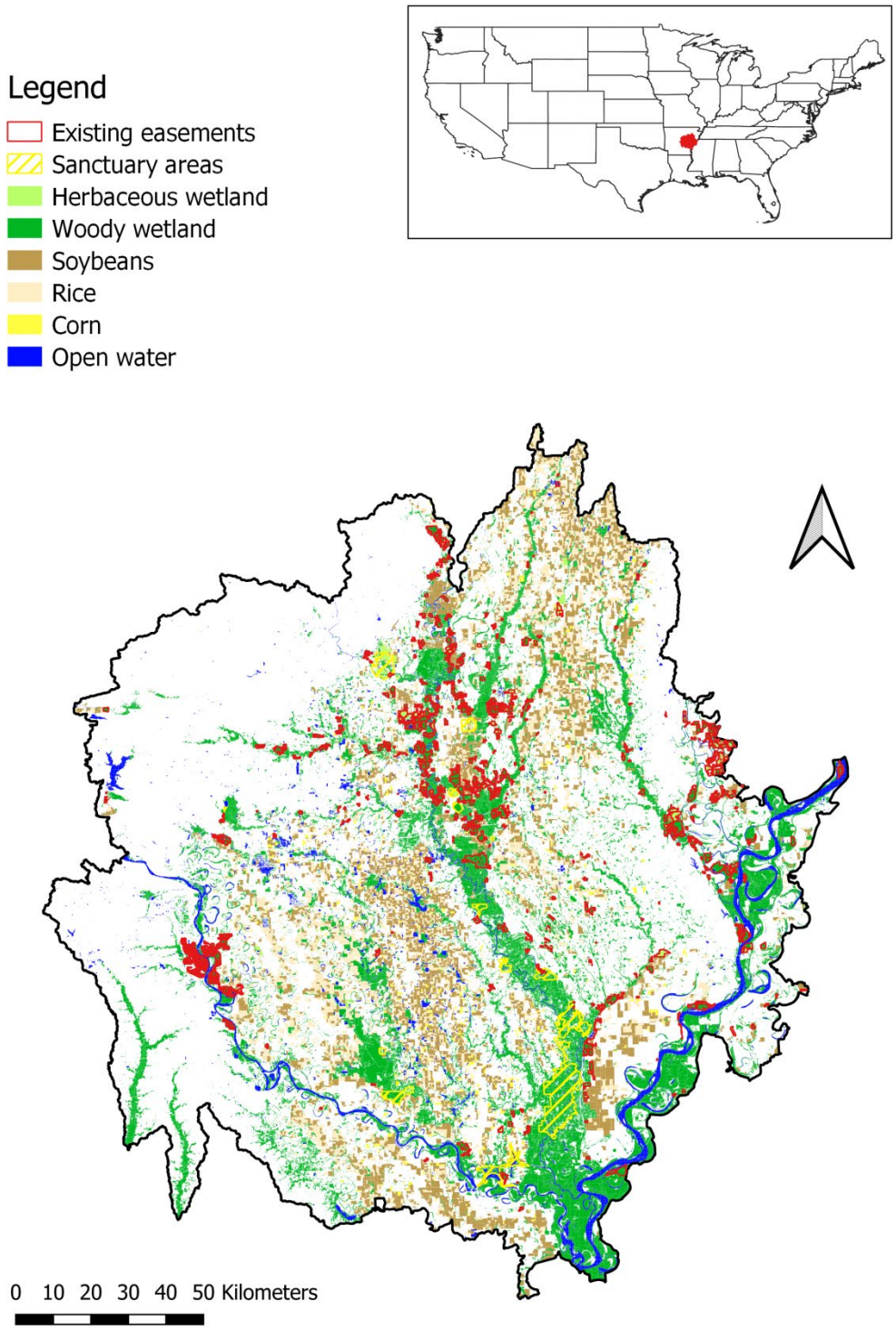


Figure II.5. Habitat type map of modeled area for the Mississippi Valley Alluvial (MAV) mallard model, with all areas assumed not to be used by foraging mallards removed (non-parameterized; white). Parameterized area: 9,732 km^2 (33.2% of total area). Easement (red) and sanctuary areas (yellow) are distinguished by colored outlines. Inset shows location within continental United States.

Food biomass and energy values

The habitat types provide different amounts of food biomass of specific energy values to agents. Table III.1 lists the values applied to each patch type and the data sources. The majority of listed values were collated in Gray et al. (2013). Herbaceous wetlands have much greater biomass than woody wetlands (33.1–77.6 g/m^2 vs 4–18 g/m^2), but slightly lower energy values (~2.5 kcal/g vs ~2.9 kcal/g). Harvested crops also have low biomass (5.5–9.4 g/m^2), but greater energy values (2.9–3.7 kcal/g). For both woody and herbaceous wetlands, managed status translated into a significant increase in biomass (woody: from 3.96 g/m^2 to 10.24 g/m^2, herbaceous: from 42.8 g/m^2 to 77.6 g/m^2). Restored herbaceous wetlands have lower biomass than unmanaged ones.

Food energy values (kcal/g) and biomass (g/m^2) provided in the literature generally pertain to plant material only (seeds, roots, and tubers). However, Gray et al. (2013) also provide separate biomasses for invertebrates, with a general invertebrate energy value (0.95 kcal/g). In most included habitats, invertebrate biomass was somewhat lower than plant biomass, and should therefore be foraged less frequently (Gray et al. 2013). Because SWAMP currently has no capacity for proportionate foraging on foods of unequal availability in the same patch, plants and invertebrates were combined into a single food item: combined biomass was calculated as the sum, and combined energy value was calculated as

$$plant\ energy\ value + \frac{invertebrate\ biomass\ \times invertebrate\ energy\ value}{plant\ biomass}$$

thus increasing energy value proportionally to invertebrate contribution to total biomass. Note that because no information was available about invertebrate biomass in woody wetland under different red oak percentages, the same proportion is used for all three woody wetland classes, resulting in a slight lowering of energy value with increasing biomass.

At model start, patches were assigned a food biomass sampled from a gamma distribution around the provided mean. We used gamma distributions to model food biomass because it is a continuous, positive distribution that can generate a range of realistic food biomass values. Standard deviations for biomass distributions were taken or calculated from the studies indicated as sources for the mean values in Gray et al. (2013), and, in some cases, rescaled to biomass from the most applicable case if no direct sourcing was available (see footnotes in Table II.1). Note that no variance specific to invertebrate biomass was considered because this it was generally not available (however, plant biomass variance is applicable to combined biomass, as standard deviations are invariant to addition of constants to the set).

Biomass was subject to a habitat-specific decay rate that represents the gradual diminishing/decomposition of food supplies through processes not represented by agent foraging. Decay rates are given as multipliers that are applied per second. As for starting distribution, decay rates strictly apply to plant biomass only, but were retained for combined biomass in absence of invertebrate-specific data.

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Table II.1. Food biomass, energy content, and decay rate values for habitat types used in the map of the Mississippi Alluvial Valley (MAV) mallard model. Sourcing and/or explanatory notes are given as footnotes.

Habitat type	*Patch type*	*Energy content (plant) (kcal/g)*	*Mean biomass (plant) (g/m^2)*	*SD of biomass*	*Energy content (invert.) (kcal/g)*	*Mean biomass (invert.) (g/m^2)*	*Combined energy content (kcal/g)*	*Combined biomass (g/m^2)*	*Decay rate (biomass multiplier, s^{-1})*
Woody wetland	20% red oak	2.76 [a]	3.8 [a]	2.78 [b]	0.95 [a]	1.14 [a]	3.05	3.94	0.999999991640947 [h]
Woody wetland	40% red oak	2.76 [a]	9.1 [a]	6.66 [b]	0.95 [a]	1.14 [a]	2.88	10.24	0.999999991640947 [h]
Woody wetland	70% red oak	2.76 [a]	16.9 [a]	12.37 [b]	0.95 [a]	1.14 [a]	2.82	18.04	0.999999991640947 [h]
Herbaceous wetland	Unmanaged	2.47 [a]	40.3 [a]	26.7 [c]	0.95 [a]	2.5 [a]	2.53	42.8	0.999999979166667 [i]
Herbaceous wetland	Managed	2.47 [a]	75.1 [a]	49.7 [c]	0.95 [a]	2.5 [a]	2.50	77.6	0.999999979166667 [i]
Herbaceous wetland	Restored	2.47 [a]	30.6 [a]	15.4 [d]	0.95 [a]	2.5 [a]	2.55	33.1	0.999999979166667 [i]
Corn		3.67 [a]	7.5 [a]	9.6 [e]	0.95 [a]	0.003 [a]	as plant only [g]	as plant only [g]	0.999999946180556 [k]
Rice		3.34 [a]	8 [a]	15.6 [f]	0.95 [a]	1.36 [a]	3.5	9.36	0.999999975347222 [k]
Soybeans		2.65 [a]	4.5 [a]	5.5 [e]	0.95 [a]	1 [a]	2.86	5.5	0.999999788194444 [k]

Footnotes:

a Gray et al. (2013)
b based on Straub (2012), scaled to biomass
c Hagy and Kaminski (2012a) for managed; for unmanaged, same scaled to biomass
d Olmstead, Webb, and Johnson (2013), scaled to biomass
e Foster et al. (2010)
f Stafford et al. (2006), scaled to biomass
g invertebrate biomass in corn patches is too small to affect combined biomass or energy value
h Leach et al. (2012)
i Hagy and Kaminski (2012b)
k Nelms and Twedt (1996)

III) Scenario parameterization

This section describes model and map configurations used to simulate particular conditions or management approaches. These scenarios constitute modifications of the base map (see Methods II), but use the same agent parameterization (see Methods I C). All scenarios share a number of common setup parameters (see section A) and most were simulated as variants in four different environmental conditions (see section B).

A) Parameters common to all scenarios

Location: All scenarios were built on the same base map depicting the previously selected location in east-central Arkansas (centerpoint at 91° 26' N, 34° 40' E), with a total area of 29,353 km^2 and a total foraging area of 9,733 km^2. Some scenarios modified available foraging area.

Randomization: Randomization entered each replicate of a simulation setup through the stochastic nature of flooding, expressed as a patch-level probability of 0/25/50/75/100%, and the stochastic distribution of food resources around a fixed mean. Under active randomization, this process ensured that every replicate run features a different mosaic of exploitable foraging patches on the landscape. We ran a sufficient number of replicates to ensure that the possible outcome space was well covered.

Replication: We conducted a power analysis to determine the number of replicates required to provide the range of outcomes. We selected five output metrics of fundamental interest: population abundance, wetland food energy, mean mallard energy intake, mean lipid storage, and mean daily foraging flight distance. We ran 240 replicates of the base map simulation under the assumption that this would be sufficient to represent the full range of possible outcomes. The maximum and minimum value for each metric was censored. The resultant range of outcomes was designated the "outcome space". We then set a target of covering 99% of the outcome space across 90% of all replicates for each of the five metrics on the last day of the simulation (day 120). We found that the use of **136 replicates** allowed us to meet this threshold with a likelihood of respectively 95% (population abundance), 96% (wetland energy), 90% (energy intake), 91% (lipids), and 97% (flight distance). This number of replicates was thus used for each landscape scenario.

Scaling: To enable running the required number of replicates with available resources, simulation speed had to be increased and memory usage reduced. To this end, we employed the SWAMP model's capability to "scale down" simulations (see Methods I A for details). We chose a **scaling factor of 1/100** that had previously been determined to yield substantial increases in efficiency without loss of outcome accuracy. At this scaling, replicates required a mean runtime of 4 h each (~544 hours per scenario). Scenarios were run at high parallelization on a remote access computing cluster to mitigate this time requirement.

Simulation duration: We used a uniform duration of **120 days,** which represented the period from November 1 to March 2. In the following, we only refer to simulation days, with day 1 representing November 1, day 2 representing November 2, etc. We chose this period because it covers most of the wintering period and provides ~1 month before and after the duck hunting season in Arkansas. Because hunting was not implemented in the model, there was no interaction with hunting disturbance or mortality; however, the designation of the first 30-day period as November governed the sequence of agent insertion into the model (see below).

Foraging times: Mallards were assumed to principally feed at night and roost during the day. Agents thus departed to forage in the afternoon and would return in the late morning, or earlier when sated. The activity period was set to **16 hours, from 17:30-9:30**. The fixed times ensured that all agents used the same daily schedule. Note that in all scenarios, mallards invariably reached satiation long before reaching maximum foraging duration, and returned to roost within ~2 hours (see section IV).

Refuge distribution and refuge selection: Mallards were able to forage on all flooded foraging patches during their active period, but returned to roost on specific refuge patches during their rest period. Refuge patches were forageable patches with 100% flooding probability that were also marked as refuges. All scenarios used **225 refuges**, the number and distribution of which was determined in the process of tuning the model to the desired output of flight distance distributions (150 in sanctuary areas and 75 distributed among sub-basins; see Methods I D). When mallards were first added to the simulation during November (see below), they were distributed among refuges proportional to refuge area.

Starting population size and mallard arrival: We used a nominal starting population size of **212,500 mallards**, which represents the median of Arkansas Mid-Winter Count numbers for the period 1981-2016 (USFWS 2016), scaled to simulation area. We added groups of immigrating mallards from November 1 – November 30, and we based the daily proportion of immigrating mallards on empirical data (Krementz, Asante, and Naylor 2012; Beatty et al. 2014). We found that the number of mallards migrating south below a latitude of 45° N tracked in these studies followed a sigmoid distribution that was steepest throughout November and leveled out at the end of the month, at which point 70% of individuals had made the relocation (Figure III.1). We therefore decided to model mallards as arriving throughout November at a proportional rate following this distribution, ending immigration on November 30 (day 30). The adapted immigration sequence, adding up to the chosen total population size, is given in Table III.1. No further individuals were added at any later point. The total population on day 30 was generally lower than the nominal starting population because some individuals often had already left the simulation over the course of November.

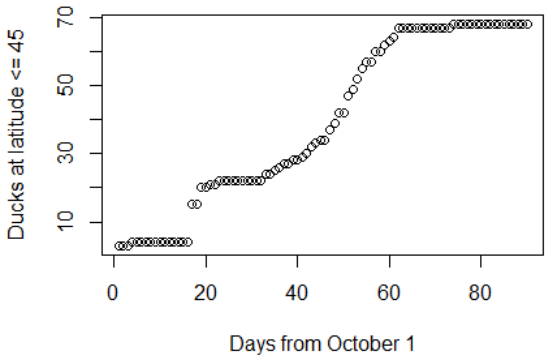


Figure III.1. Percentage of mallards from two sets of satellite-tracked individuals (Krementz, Asante, and Naylor 2012; Beatty et al. 2014) that were located at latitudes ≤ 45° N after October 1, combined over multiple years.

Table III.1. Daily number of immigrating mallards added to the Mississippi Alluvial Valley (MAV) mallard model over the first month of each run (day 1–30).

Day	*# added*	*Day*	*# added*	*Day*	*# added*	*Day*	*# added*	*Day*	*# added*
1	68,750	*7*	3,125	*13*	6,250	*19*	9,375	*25*	6,250
2	0	*8*	0	*14*	3,125	*20*	0	*26*	0
3	6,250	*9*	3,125	*15*	3,125	*21*	15,625	*27*	9,375
4	0	*10*	0	*16*	0	*22*	6,250	*28*	8,300

5	3,125	*11*	3,125	*17*	9,375	*23*	9,375	*29*	8,300
6	3,125	*12*	3,125	*18*	6,250	*24*	9,375	*30*	8,400

To ensure a realistic rate of exploitation of food resources, a number of "non-mallard" dabbling ducks were included in all scenarios to represent waterfowl of other species also foraging on the landscape. Mallards are the most numerous wintering species in the region, and the ratio of mallards to all other waterfowl is roughly 1:1 (USFWS 2016). We therefore included **an equal number of generalized "non-mallards"**, immigrating with the same timing. In the absence of type-specific parameterization for these agents, they were parameterized as mallards in all respects, but were not evaluated in outcome metrics. An exception were some metrics directly connected with total landscape energy that took "all species" into account (total demand, total intake, and days to deficit).

For the evaluation of model results, all data series were left-truncated on day 30, excising the first 29 days of simulation (November) because the repeated addition of new individuals during that time largely obscured any visible dynamics. All inference was thus based on the 90-day period between day 30 and day 120 only.

B) Environmental conditions

We assumed that the simulated area would be subject to changes in environmental conditions outside the control of active management. The model simulates different global flooding regimes, corresponding to flood, standard, weak drought, and strong drought conditions on wetlands. These conditions were represented as mapwide increases or decreases in each patch's flooding probability (in the following, **FP**), were in effect for the entire run duration, and could be applied independent of the specific scenario being simulated. Because effects of management actions might vary under different flooding regimes, we investigated the outcomes of most scenarios under the same range of variations in environmental conditions. Note that several scenarios or types of scenarios were not simulated under all conditions (noted in the scenario description). Table III.2 shows mean FP for all foraging habitat classes under the different environmental conditions on the base map.

Standard conditions (overall mean patch FP: 37%) represented average landscape conditions in most years. They were based on mean foraging patch FPs derived from the Southeast Floodplain Inundation Frequency map (Allen 2016), stratified into levels of 0/25/50/75/100%. Under standard conditions, a large percentage (~25%) of patches classified as forageable wetlands based on NLCD data actually had a FP of 0% and were not available to mallards; see Methods II for details. These are treated as potentially available only under flood conditions (below).

Flood conditions (overall mean patch FP: 59%) represented natural high inundation conditions where an abundance of flooded habitat is available. We assumed that FP of all foraging patches would be increased by 25%, to a maximum of 100%. This includes 0%-flooded wetlands; the available foraging area under flood conditions was thus substantially larger than under standard conditions.

Weak drought conditions (overall mean patch FP: 31%) represented moderate food scarcity conditions under lower than normal inundation. FP of all patches with 75% or 100% FP was reduced by 25%, while patches with lower FP were not modified. Thus, maximum FP on the map was 75%, and no patches would be allowed to newly become entirely un-floodable (FP 0%).

Strong drought conditions (overall mean patch FP: 19%) represented severe food scarcity conditions under substantially lowered inundation. FP of all patches was reduced by 25%, resulting in many patches becoming entirely un-floodable and a greatly decreased foraging area.

Table III.2. Mean flooding probability on the base map of the Mississippi Alluvial Valley (MAV) mallard model for areas of each foraging habitat type, under the four simulated environmental conditions (standard, flood, weak drought, strong drought).

Habitat type	***Standard conditions***	***Flood***	***Weak drought***	***Strong drought***
Mapwide mean	0.37	0.59	0.31	0.19
Herbaceous wetland (all types)	0.42	0.62	0.34	0.23
Woody wetland (all types)	0.35	0.57	0.29	0.19
Crops (all types)	0.43	0.66	0.38	0.18
Herbaceous wetland (unmanaged)	0.39	0.59	0.31	0.23
Herbaceous wetland (managed)	0.51	0.69	0.42	0.26
Herbaceous wetland (restored)	0.47	0.68	0.40	0.22
Woody wetland (unmanaged / 20% red oak)	0.35	0.57	0.29	0.19
Woody wetland (managed / 40% red oak)	0.24	0.48	0.20	0.13
Oak-rich woody wetland (70% red oak)	0.46	0.70	0.39	0.25
Soybeans	0.41	0.64	0.36	0.16
Rice	0.49	0.70	0.41	0.24
Corn	0.37	0.61	0.34	0.12

C) Management scenarios

Scenarios were developed to answer questions related to the future management of conservation easements for the benefit of waterfowl. These can be arranged in four broad groups.

1) Absence of easements / easement management
2) Increasing easement area at random locations
3) Increasing easement area at selected locations
4) Enhancing management of wetlands in existing easements

In the context of these scenarios, “management” is intended to encompass the wide range of wetland management techniques that may be used by landholders to provide habitat diversity and high food biomass production for the benefit of waterfowl (Gray et al. 2013). When applied to herbaceous wetlands, these may include active approaches such as disking, mowing, herbicide application, burning, or targeted cattle grazing; or passive methods such as timed water drawdowns to promote desirable vegetation, or to provide seasonal mudflat habitat. Hydrology manipulation may consist of using levees, reservoirs and flood control measures. Management may be specifically aimed at maintaining early successional plant communities because these have greater seed and tuber production. For woody wetlands, approaches may include hydrologic restoration by impoundments or floodplain connectivity, and silviculture practices like selective thinning and replanting to increase the proportion of trees

producing desirable waterfowl food crops (e.g., red oak species). For the purpose of the simulated scenarios, it was assumed that managers would apply suitable techniques from this range to achieve the desired goal of manipulated hydrology and/or food biomass availability. The area that management actions were applied to (stated for each scenario) was not based on cost or feasibility calculations but chosen to affect what was considered representative fractions (e.g., 25% of a certain type of wetlands in easements).

Scenarios developed for each group are described below. Table III.3 shows the list of scenarios that were run as combinations of management scenarios and environmental condition cases. A total of 54 different scenarios were tested. Maps including habitat distribution statistics and tabular data (foraging area and proportions, flooding details, and food energy, by habitat) for each scenario are available from the corresponding author on request.

1) Absence of easements / easement management

These scenarios simulate situations in which current conservation and management practices are reduced or absent, with the aim of estimating the benefit derived from currently existing management. Here, wetlands in easements were downgraded to a lower or absent management status, or reverted to their pre-restoration status.

- No wetland management in easements: represented lack of extra management of wetlands in easements. All managed herbaceous wetlands in easements were set to unmanaged status, lowering their available food biomass. Woody wetlands remained unchanged because it is assumed that changes in oak forage percentage are slow to respond to management practices. This affected 0.6% of the total foraging area.

- No easements: represented a condition where easements were never established in the first place; thus, restoration of crops to restored wetlands did not happen and existing wetlands did not receive increased management. In all easements, all restored herbaceous wetlands were converted to harvested crops (randomly chosen from rice, corn, or soybeans) and all managed herbaceous or woody wetlands were set to unmanaged. Current unmanaged wetlands were retained. We assumed that it is unusual for non-crops (e.g., pasture) to have been restored to wetlands in easements, so wetlands were not turned into non-habitat patches (which would be omitted from map representation). This affected 1.2% of the total foraging area.

2) Increasing easement area at random locations

These scenarios categorize existing foraging patches as easements to add new easement area. In all increased area scenarios, new easement patches were established until an increase in total easement area equal to 25% (154 km^2) of the current easement area was achieved, equating to 1.5% of the total foraging area. Affected crop patches were converted to restored wetlands; pre-existing wetlands were retained as unmanaged wetlands (managed wetland status in easements was only assigned if it was already recorded in the databases, or if a scenario expressly simulated that upgrade). If the FP of restored patches was 0%, it was raised to 25%, since it was assumed that wetlands subject to targeted restoration can be assured of at least intermittent flooding.

In the "random" group of area increase scenarios, additions were selected under the assumption that acquisition happens opportunistically, i.e. that the location of the additional areas is essentially random.

● New easements: represented the approach of establishing entirely new contiguous easements that are not derived as extension of already existing ones. Depending on the scenario specifications, new easements were established as either small units, with a target area equal to the median size of existing easements (0.69 km^2), or as large units, with a target area equal to the 3rd quartile of existing easements (1.62 km^2). The first approach resulted in more numerous, smaller easements, the latter in fewer, larger ones. In either case the total added easement area summed to 154 km^2, which equaled 25% of existing area. Target easement size was defined by a circle of the desired area, and foraging patches overlapped by the circle were combined into the new easement. New easements were placed at random locations centered on an existing foraging patch (wetland or crops), and no two locations were closer than one target easement diameter (i.e., easements could not overlap).

To ensure a representative composition of newly established easements, we used data from the NEST database to calculate the proportion of restored agricultural cropland versus pre-existing wetlands in existing easements in the modeled area. We found that on average, 69% of easement area (with a range of 12%–100%) consisted of converted agricultural land, while the remainder consisted of parcels that were recorded as existing wetlands at the time of the easement agreement. We therefore made sure that the total area of newly established easements had a comparable composition of 69 ± 2% restored wetlands (former crops) versus 31 ± 2% pre-existing wetlands.

● Roundout of existing easements: represented the approach of adding new easement area by extending the contiguous area of existing easements. New foraging patches (crops and wetlands) that directly border a "seed" easement were added to it, and their types and flooding probability were adapted as described above. Roundout also was carried out in either small units or large units scenarios. Small unit roundout consisted of adding all foraging patches that directly bordered the seed easement. Large unit roundout then added a second layer of patches bordering the first layer. Again, the first approach resulted in more numerous, smaller enlarged easements, the latter in fewer, more substantially enlarged ones. Due to the variable size of seed easements and patches, no target sizes were set for individual roundouts, but the constant total added area of 154 km^2 was observed. Seed easements were chosen at random.

Because it was assumed that in easement enlargement by roundout, choice of added land parcels was more strongly dependent on local landscape configurations, we did not enforce any ratio of restored versus existing wetlands. The proportion of restored cropland in the added area in these scenarios was thus lower (mean 38%) with a wider range (34.1–43.9%) than the target ratio used in the 'new easement' scenarios (above).

3) Increasing easement area at selected locations

These scenarios add new easement area as described above, but under the stipulation that patch choice is restricted to particular locations, with the intention of increasing the effectiveness of management actions. Both of the below scenarios were done in small unit and large unit variants, as described above, and the same total area (25% of existing easement area) was added. These

scenarios were only tested under standard conditions (no flood, weak drought, or drought variants) due to computing resources constraints.

● Placement close to sanctuaries: represented choice of new easement locations, or seed easements for roundout, in close proximity to existing sanctuary areas. Selected locations were restricted to a buffer of 15 km around sanctuary areas. Placement close to sanctuaries assumed that foraging areas proximate to disturbance-free roosting and foraging locations has a net energy payoff (however, note that hunting disturbance is not currently implemented in the model).

● Use of NWI patches only: represented selection of only additional patches that were identified as wetlands in the 2019 NWI database. This dataset was not used to parameterize patch type in the present model because much of its information is out of date for the MAV, dating from the 1980s or earlier. But these spatial data makeit a useful historical reference for the presence of former wetlands. Crop patches converted to restored wetlands under these restrictions are likely to once have been wetlands and may in reality represent particularly good restoration candidates. However, this benefit to practical management is again not represented in the simulation. A minor secondary benefit was more likely placement in proximity to areas of existing wetlands (most of which were also in the NWI database).

4) Enhancing wetland management in existing easements

These scenarios do not add land acquisitions to easements but rather focus on increasing the active management of existing easements. The first group of this type deals with enhancing the amount of food biomass in easement wetlands. If affected wetlands had 0% FP, they were also upgraded to 25%.

● Increased wetland management 25%, all types: represented increased management practices applied to 25% of existing unmanaged woody and herbaceous wetlands in easements (randomly selected). Affected wetlands were upgraded to managed status, increasing food biomass (42.9 g/m^2 to 77.6 g/m^2 for herbaceous wetland, 3.9 g/m^2 to 10.2 g/m^2 for woody wetland). This affected 1.5% of the total foraging area.

● Increased wetland management 25%, herbaceous only: as above, but only herbaceous unmanaged wetlands were upgraded, under the assumption that management for waterfowl forage would yield quicker results in herbaceous than in woody wetlands (moist-soil management vs forest composition change). This affected 0.3% of the total foraging area.

● Intensive wetland management 50%, herbaceous only: represented an approach of expending special effort on maintaining the most valuable wetland resources. Here 50% of *already managed* herbaceous wetlands in easements were improved further by making sure that a consistently large amount of food was available. This was done by replacing the standard stochastically determined food amount (gamma-distributed with SD = 49.7 around a mean of 77.6 g/m^2) with a larger fixed amount, at the 3rd quartile level of the original distribution (103 g/m^2). This affected 0.4% of the total foraging area. The scenario was only tested under standard environmental conditions.

The second group of enhanced management scenarios deals with increasing the availability of existing foraging patches by manipulating flooding in easements. Because these scenarios were intended to only enhance FP under less than abundantly flooded conditions, they were not tested under flood conditions.

● Consistent flooding: represented an approach of ensuring that generally available foraging patches were consistently available. All foraging patches in easements that had 50% or 75% FP were upgraded to 100% FP. This affected 1.6% of the total foraging area.

● Consistent minimum flooding: represented an approach of preventing foraging patches from becoming completely un-floodable even in a drought. Under strong drought conditions, all foraging patches in easements were instead subjected to a weak drought effect, thus lowering FP by 25% for patches at 75% or 100% FP only instead of for all patches. (Expressed another way, this constituted drought protection for patches with ≤ 50% FP.) Consequently, the scenario was only tested under strong drought. This affected 5.6% of the total foraging area.

● Active flooding: represented active partial flooding via the release of stored water at a specified time in the season. This was implemented as setting 25% of the easement forage area to flooded status from that point onwards, overwriting the previous flooding status (flooded or unflooded) that had been determined via FP at the start of the simulation. Localized flooding was implemented on day 1, day 60, or day 90. This was the only management scenario that also affected the category of 0%-flooded patches, which otherwise could only be activated under global flood conditions. It affected 1.5% of the total foraging area.

Table III.3. List of management scenario runs (54) carried out in the Mississippi Alluvial Valley (MAV) mallard model. Proportion affected: proportion of total foraging area affected by manipulation implemented by scenario.

Scenario name	*Scenario type*	*Foraging area affected by manipulation*	*Proportion affected*
No wetland management in easements	decreased management	all managed herbaceous wetlands in easements	0.6%
No wetland management in easements & flood	decreased management	all managed herbaceous wetlands in easements	0.6%
No wetland management in easements & weak drought	decreased management	all managed herbaceous wetlands in easements	0.6%
No wetland management in easements & strong drought	decreased management	all managed herbaceous wetlands in easements	0.6%
No easements	decreased management	all managed and restored herbaceous wetlands in easements	1.2%
No easements & flood	decreased management	all managed and restored herbaceous wetlands in easements	1.2%
No easements & weak drought	decreased management	all managed and restored herbaceous wetlands in easements	1.2%
No easements & strong drought	decreased management	all managed and restored herbaceous wetlands in easements	1.2%
New easements +25% (large units)	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (large units) & flood	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (large units) & weak drought	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (large units) & strong drought	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (large units), close to sanctuaries	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (large units), NWI patches only	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (small units)	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (small units) & flood	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (small units) & weak drought	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (small units) & strong drought	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
New easements +25% (small units), close to sanctuaries	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%

Table III.3. continued.

Scenario name	*Scenario type*	*Foraging area affected by manipulation*	*Proportion affected*
New easements +25% (small units), NWI patches only	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (large units)	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (large units) & flood	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (large units) & weak drought	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (large units) & strong drought	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (large units), close to sanctuaries	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (large units), NWI patches only	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (small units)	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (small units) & flood	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (small units) & weak drought	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (small units) & strong drought	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (small units), close to sanctuaries	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%
Roundout +25% (small units), NWI patches only	additional easement area	non-easement foraging area equal to 25% of easement foraging area	1.5%

Table III.3 continued.

Scenario name	*Scenario type*	*Foraging area affected by manipulation*	*Proportion affected*
Increased wetland management 25% (all types)	increased management	25% of easement wetland area	1.5%
Increased wetland management 25% (all types) & flood	increased management	25% of easement wetland area	1.5%
Increased wetland management 25% (all types) & weak drought	increased management	25% of easement wetland area	1.5%
Increased wetland management 25% (all types) & strong drought	increased management	25% of easement wetland area	1.5%
Increased wetland management 25% (herbaceous)	increased management	25% of easement herbaceous wetland area	0.3%
Increased wetland management 25% (herbaceous) & flood	increased management	25% of easement herbaceous wetland area	0.3%
Increased wetland management 25% (herbaceous) & weak drought	increased management	25% of easement herbaceous wetland area	0.3%
Increased wetland management 25% (herbaceous) & strong drought	increased management	25% of easement herbaceous wetland area	0.3%
Intensive wetland management 50% (herbaceous)	increased management	50% of already managed easement herbaceous wetlands	0.4%
Consistent flooding	enhanced flooding	all easement wetlands with flooding probability ≥ 50%	1.6%
Consistent flooding & weak drought	enhanced flooding	all easement wetlands with flooding probability ≥ 50%	1.6%
Consistent flooding & strong drought	enhanced flooding	all easement wetlands with flooding probability ≥ 50%	1.6%
Consistent minimum flooding & strong drought	enhanced flooding	all easement wetlands with flooding probability ≤ 50%	5.6%
Active flooding (day 1)	enhanced flooding	25% of easement wetland area	1.5%
Active flooding (day 60)	enhanced flooding	25% of easement wetland area	1.5%
Active flooding (day 90)	enhanced flooding	25% of easement wetland area	1.5%
Active flooding (day 1) & weak drought	enhanced flooding	25% of easement wetland area	1.5%
Active flooding (day 60) & weak drought	enhanced flooding	25% of easement wetland area	1.5%
Active flooding (day 90) & weak drought	enhanced flooding	25% of easement wetland area	1.5%
Active flooding (day 1) & strong drought	enhanced flooding	25% of easement wetland area	1.5%
Active flooding (day 60+) & strong drought	enhanced flooding	25% of easement wetland area	1.5%
Active flooding (day 90) & strong drought	enhanced flooding	25% of easement wetland area	1.5%

Results and Discussion

IV) Seasonal dynamics of simulation output metrics: base scenario output in context

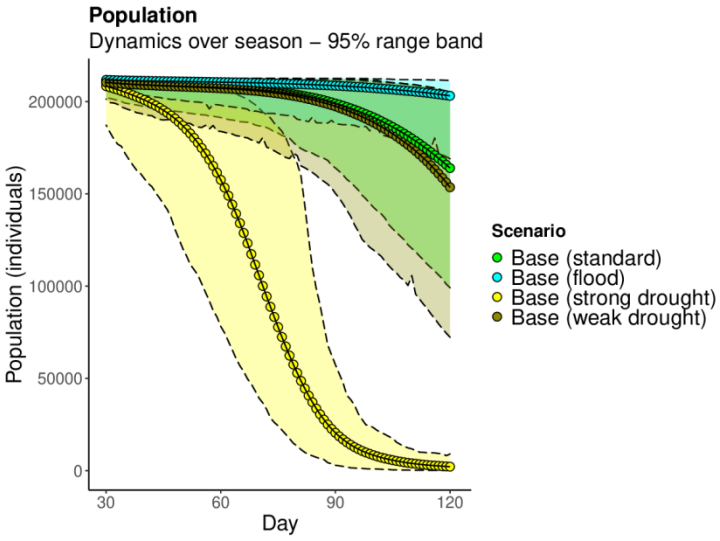
This section presents an overview of output metric dynamics from November 1 to March 2. Dynamics for each metric are shown using the base scenario (136 replicates, showing median and 95% data range) under the four modeled environmental conditions: standard, flood, weak drought, and strong drought. The aim of these figures is to provide a baseline for the behavior of each metric over the course of the season, which is then modified in the management scenarios discussed in section II, and to illustrate the causal relationships among metrics.

We here discuss only a subset of available metrics that was considered particularly informative: population abundance, emigration, mean forage flight distance, mean lipid storage, and forage time proportion in the different habitats. A figure showing the dynamics of a greater range of recorded metrics is available from the corresponding author on request. Table IV.1 provides a list and a short description of these metrics. All data series were left-truncated on day 30, and interpretation of the results was based on the 90 day period between day 30 and day 120 only (see Methods III A).

Table IV.1. Unit and description of selected output metrics of the Mississippi Alluvial Valley (MAV) mallard model

Metric	***Unit***	***Description***
Population	individual	Number of mallards present on map
Emigration	individual	Number of mallards that leave the simulation because their lipid storage drops below the emigration threshold
Mean lipids	kcal	Mean body fat storage of a mallard
Mean forage flight distance	m	Mean distance for a mallard to get from the roosting site to the first foraging patch of the day
Forage time proportion: herbaceous wetland, woody wetland, crops (soybeans, rice, corn)	%	Mean proportion of a mallard's forage time that is spent in patches of the indicated type

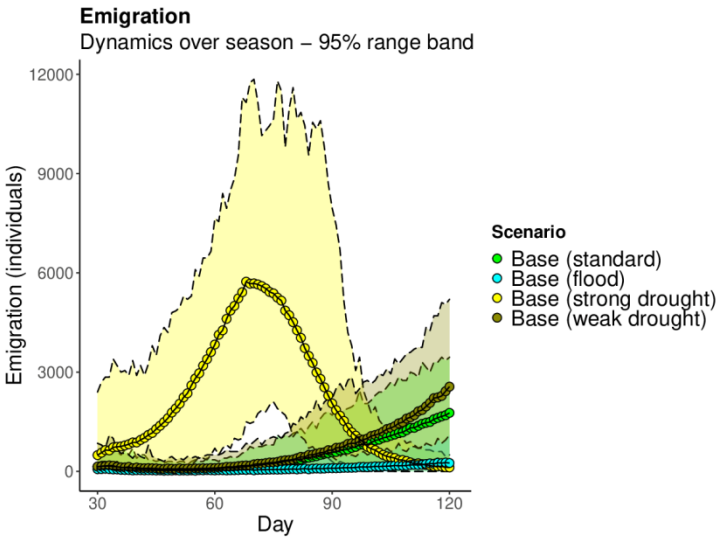
Figure IV.1



Population: the number of mallards present on the map during the 120 day model simulation under different environmental scenarios (Figure IV.1). The shaded areas (range band) represent bilateral 95% value ranges.

Populations declined under all conditions due to emigration from the simulation. The decline was slower under flood conditions than base conditions, generally stronger under weak drought than base, and much more rapid under strong drought, where numbers may reach 0 (entire population emigrated). In all scenarios, the population on day 30 following the last daily immigration event, was the maximum reached during the scenario, although this was almost always lower than the nominal total number added (because some mallards may already exit the simulation during days 0–30). Outcome variance across replicates increased over the season, except when the population was rapidly dwindling.

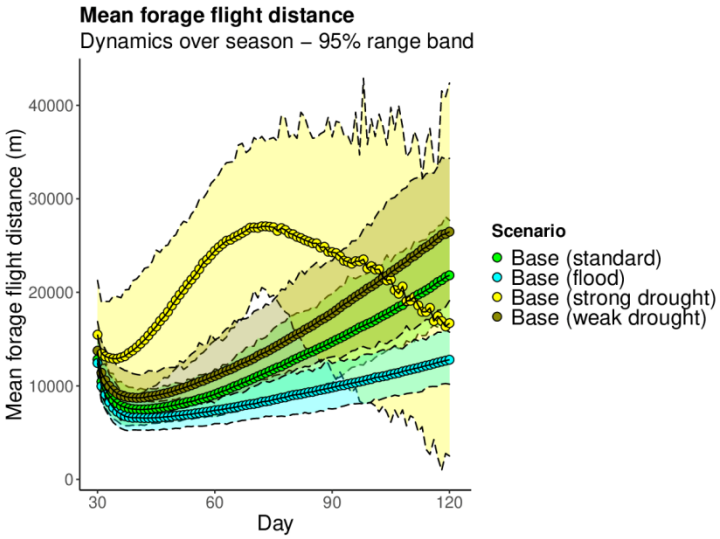
Figure IV.2



Emigration: the number of mallards that decide to leave the area during the 120 day model simulation under different environmental scenarios because their stored energy drops below the emigration threshold (Figure IV.2). The shaded areas (range band) represent bilateral 95% value ranges.

Under most conditions, emigration continually increased over the season as food availability declined. The increase was slower under flood and more rapid in drought conditions. Under strong drought, there was generally an early peak in daily emigration followed by a decline (possibly to zero). This is a result of the population dropping rapidly – although the *proportion* of mallards present that emigrate was still high or increasing, the absolute number of emigrations dropped, and may reach zero when all ducks have exited. Outcome variance across replicates increased over season, except when the population was rapidly dwindling.

Figure IV.3

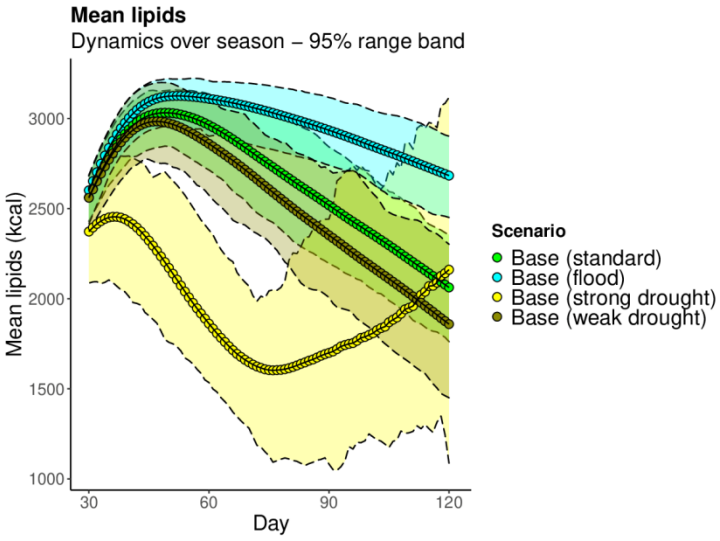


Mean forage flight distance: the mean distance (m) that a mallard travels from the roosting site to the first foraging patch of the day during the 120 day model simulation under different environmental scenarios (Figure IV.3). The shaded areas (range band) represent bilateral 95% value ranges.

Flight from roost to first foraging patch, or last foraging patch to roost, made up the majority of movements of a mallard in the simulation; in conditions when there was little switching between depleted patches during a foraging bout (i.e., except for the late stages of strong drought scenarios), it comprised almost all movement. This metric was a good indicator of ease of food access at any point. It dropped to a minimum in the early season when mallards settled into optimal early exploitation positions, then increased when patches close to roosts became depleted and patches with high food energy became more sparse on the map. Under strong drought conditions, flight distance may peak and then decline when the population has dwindled to a few mallards exploiting the best remaining patches.

Mean lipids: the mean body fat storage (kcal) of a mallard during the 120 day model simulation under different environmental scenarios (Figure IV.4). The shaded areas (range band) represent bilateral 95% value ranges.

Figure IV.4



Lipids were added to an individual's lipid store before the start of a day's foraging bout if the duck had excess food energy left from the previous day and night. Energy was drawn from the lipid store whenever there was an energy demand but the mallard had no active food energy (if this happened when the store was empty, the mallard died). Each individual had a storage limit of 3,463 kcal, which may be reached under flood conditions. Mallards entered the simulation without lipids but created a store on day 1 based on their (randomized) starting energy.

Each day's first flight, before the first foraging patch was reached, must be "paid for" from lipids, because all remaining food energy was just converted to storage. This was a daily lipid drain that happened even when the store was otherwise being built up, and accounted for the lipid store decrease that happened in all scenarios even if **net energy gain** remained positive throughout.

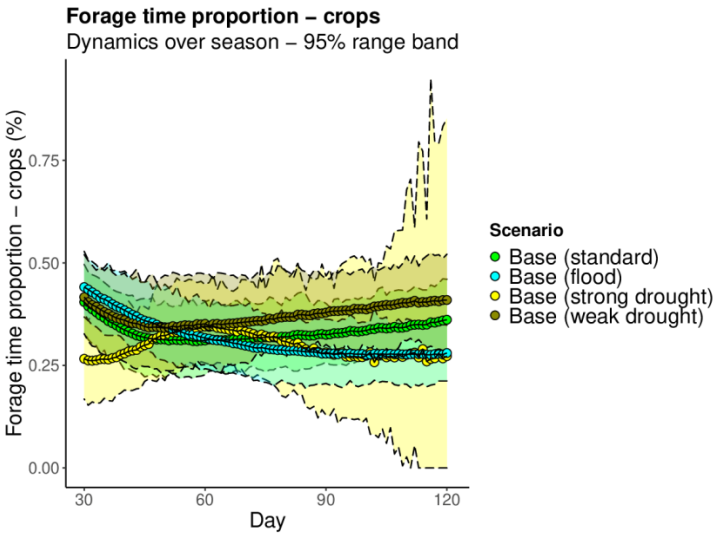
Under all conditions, lipids initially increased as mallards exploited crops that yielded excess energy. When mallards began to switch to less energetic, but more plentiful wetland food resources and flight demand energy increased, lipid stores peaked and began to be depleted (day 50–60), which then continued throughout the season. In strong drought conditions, mean lipid storage might increase late-season as the population dwindled and individuals with low stores exited the map.

The storage threshold for triggering migration was 513 kcal (15% of maximum storage). Note that this level is outside the range displayed in Figure IV.4, since emigrating individuals were always those with the lowest lipids stores (i.e. below the 95% range displayed).

Forage time proportions record the mean proportion of a mallard's **foraging time** spent in different flooded habitat patches. The maximal foraging time available each day was 16 hours (see section III A); however mallards invariably reached their individual satiation threshold (137.5 g) well before that time, at which point they returned to roost. The mean daily length of foraging bouts in the base scenario was 133 minutes.

Forage time proportions - crops: the mean proportion of a mallard's **foraging time** spent in flooded crop patches during the 120 day model simulation under different environmental scenarios (Figure IV.5). The shaded areas (range band) represent bilateral 95% value ranges.

Figure IV.5

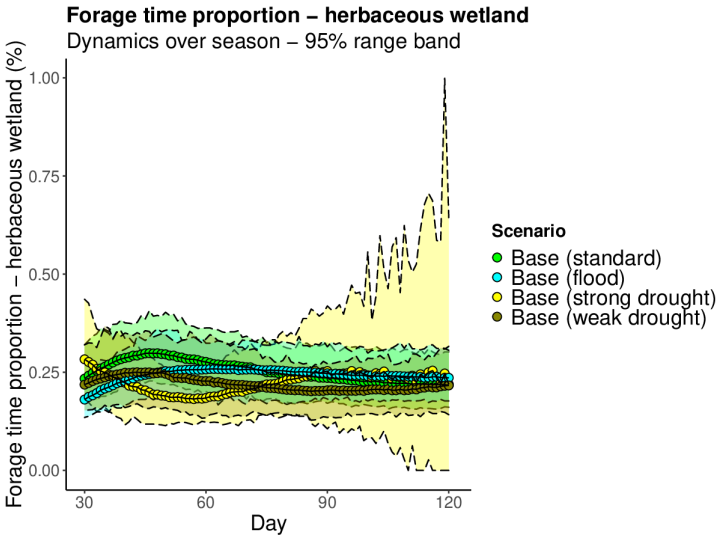


Flooded crop patches make up just under half of the total forageable area (47.4%). In comparison to herbaceous wetlands, they have little food biomass (~7.5 g/m^2 vs 33–78 g/m^2) but contain food of higher energy value (~3.4 kcal/g vs ~2.5 kcal/g; Gray et al. 2013), and are thus prioritized early by mallards.

The three represented crop types (soybeans, rice, and corn) are present in different proportions and have different biomasses per unit area, energy values, and flooding probabilities; see Methods I B and III B. **Soybeans** was the most common crop but has the lowest biomass and was depleted first. **Rice** has larger biomass and was more likely to be flooded under all conditions than the other crops (Methods III B, Table III.1), providing foraging throughout the season; rice use increased in late season as food biomass in some wetlands became depleted. The dynamics observed in the crops category as a whole tended to be driven by rice. **Corn** patches were much more rare and less likely to be flooded than the other two crop types but contained large biomass, and remained available at low but constant exploitation volume throughout the season.

Proportional use declined early in the season under all but strong drought conditions as soybean patches became overexploited and ducks shifted to wetland patches, then increased again when food biomass in wetlands became more depleted and mallards made use of the reliable late-season rice availability. Crop food biomass was subject to more rapid decomposition (over the course of the season, 22.6% for rice, 42.7% for corn, and 88.9% for soybeans) than wetlands (8.3% for woody and 19.4% for herbaceous wetlands; for sources see Table II.1), which contributed to the early-season shift to wetland foraging. Late-season crop use was lower under flood conditions because food biomass in wetlands was less likely to become depleted.

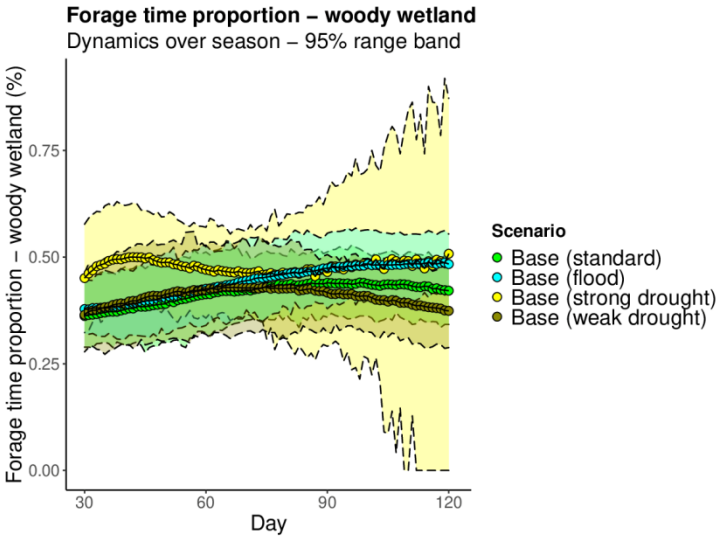
Figure IV.6



<u>Forage time proportion – herbaceous wetland:</u> the mean proportion of a mallard's **foraging time** spent in flooded herbaceous wetland patches during the 120 day model simulation under different environmental scenarios (Figure IV.6). The shaded areas (range band) represent bilateral 95% value ranges.

Herbaceous wetlands were rare in the landscape (1.7% of the total foraging area) and had lower food energy value than crops (~2.5 kcal/g) but much greater potential food biomass (~33–78 g/m^2) and were relatively likely to be flooded under all conditions (Table III.1); as a foraging category, they were slow to deplete. Proportional use increased early in the season as **soybeans** were exhausted, then leveled out to ~25% under all conditions in the base scenario.

Figure IV.7



<u>Forage time proportion – woody wetland:</u> the mean proportion of a mallard's **foraging time** spent in flooded woody wetland patches during the 120 day model simulation under different environmental scenarios (Figure IV.7). The shaded areas (range band) represent bilateral 95% value ranges.

Woody wetlands made up half of all foraging patches in the landscape (50.9% of foraging area) but have lower food energy value than crops (~2.9 kcal/g), low food biomass (~4 g/m^2), and on average had slightly lower flooding probabilities than the other foraging categories (Table III.1). Their proportional use increased until mid-season under most conditions as the crop category was depleted, then declined as the low-yield patches became depleted and mallards started switching to still productive rice fields or herbaceous wetlands

Both wetland types likely received a boost in usage proportion from the increased likelihood of proximity to sanctuaries and the main concentrations of roost sites on the map, which made them more convenient to exploit.

V) Scenario results

This section presents results from the simulations based on specific management scenarios. The scenarios were grouped under five topical questions:

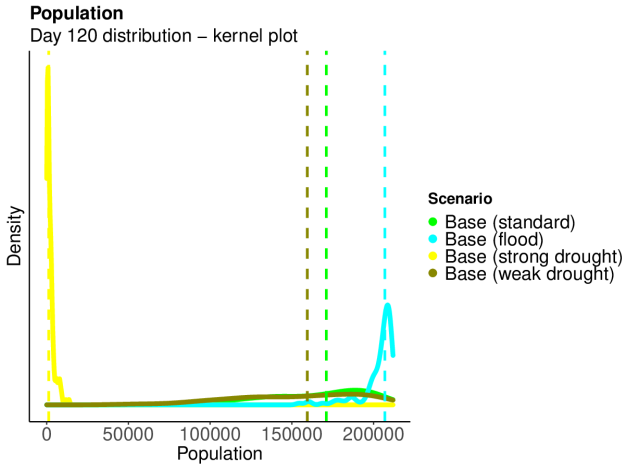
A) Absence of easements / management in easements – what is the effect of the current easement program, compared to a situation without easements or with reduced management in easements?
B) Increasing easement area at random locations – what is the effect of adding more existing wetlands and more wetlands restored from crop patches to easements, if patches are chosen opportunistically / at random?
C) Increasing easement area at selected locations – what is the effect of B) if patches are chosen based on additional location criteria?
D) Enhancing the management of wetlands in existing easements – what is the effect of enhancing the availability or biomass yield of wetlands already in easements?
E) Increasing population abundance at end of season (all management approaches) – what is the most effective choice if both area increase *and* management enhancement options are available?

The majority of scenarios were evaluated under four different environmental conditions: standard, abundance (flood), weak scarcity (weak drought), and severe scarcity (strong drought). Exceptions were the increased area scenarios with location selection (section C) scenarios and "intensive management of herbaceous wetland 50%" scenario, which were only tested under standard conditions due to restrictions on available computing resources; scenarios involving local flooding manipulation, which were not tested under global flooding due to redundancy; and the "consistent minimum flooding" scenario, which was only applicable under strong drought. Details on scenario implementation and environmental conditions can be found in Methods III.

The principal metric on which scenarios were compared was median population abundance at the end of the modeled winter season period (day 120), and specifically the difference in end-of-season population compared to the base scenario under the same environmental conditions. This comparison baseline is referred to as the **condition base** in the following. As noted in Results section I, data series were left-truncated on day 30, excluding the first 30 days of simulation (November) because dynamics during that period tended to be obfuscated by staggered addition of immigrating individuals.

Each of the following sections contains a results overview, a series of composite figures illustrating output metrics of interest, and a combined results and discussion section. Where the number of scenarios covered in a question or tested under a shared condition was too large to allow representation in the same figures, scenarios were split into two subgroups, or only the top few scenarios were illustrated in detail. In addition to the scenarios under discussion, each figure also contains the condition base for comparison. Only a selection of the most informative metrics (population abundance, emigration, mean foraging distance, lipid storage, and forage time proportion per habitat type) is shown here. A figure showing the dynamics of a greater range of recorded metrics, for each tested scenario, is available from the corresponding author on request.

Results are illustrated with three types of figures. Below these are exemplified using the base scenario under different environmental conditions.

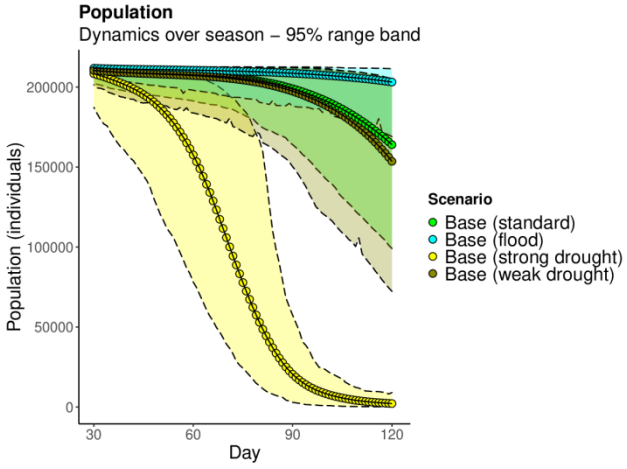


Kernel plots are probability density plots that show the frequency distribution of a metric across replicates at one time point, plotted in overlap. They show population abundance on the x-axis, and frequency density of population abundance across all replicates on the y-axis, at one time point (day 120). Medians are indicated by dashed vertical lines. These plots are useful to directly compare a limited number of scenarios in terms of median outcome and outcome distribution at the end of the season.



Violin plots are mirrored probability density plots displayed like a boxplot. They show frequency density of population sizes across all replicates on the x-axis (grouped by scenario), and population abundance on the y-axis, at one time point (day 120). An inserted boxplot shows median and 1st and 3rd quartiles of population size. Violin plots are useful to illustrate a metric's range and distribution at the end of the season in comparison among numerous scenarios. Each violin plot also contains the condition base in the far left position; all other scenarios are ordered by decreasing population gain relative to the condition base (shown as percentage underneath each violin).

(Note that each individual violin is scaled to the same width. Thus in contrast to kernel plot height, violin width is not directly comparable between scenarios.)



Dynamics plots illustrate the change in a metric over time across the whole season. They show time (day) on the x-axis, and median metric value on the y-axis. For population abundance, the dynamics plots in the following sections also show the bilateral 95% value range of outcomes across replicates as colored polygons for each scenario; for all other metrics, only the 95% range of the condition base is shown. These plots are useful to show differences in change over time between scenarios (see also Results section I).

A) Absence of easements / management in easements

These scenarios illustrate the additional number of mallards that may be sustained in the area by current conservation and management practices, by contrasting two scenarios where benefits of easements are reduced or absent. In the first scenario, easements exist but **easement wetlands receive no management**. Here, all herbaceous wetlands in easements were set to the lower-yield unmanaged state. Woody wetlands remained unchanged because it was assumed that changes in oak forage percentage are slow to respond to management practices. In the second scenario, **no easements** exist; habitats were treated as if easements were never established. All managed herbaceous and woody wetlands were set to unmanaged, and all restored herbaceous wetlands were converted to a randomly chosen crop type.

Outcomes: (compared to **condition base**)

Scenarios yielded additional population losses at end of season from -12% (strong drought; -150 mallards) to -80.9% (weak drought; -123,450 mallards). Losses were more severe for complete absence of easements than for absence of wetland management only.

Table V.1. Metrics of total population abundance at end of season (day 120) in the Mississippi Alluvial Valley (MAV) mallard model, for scenario group A. %Cco: % change from condition base (base scenario under relevant environmental conditions: Standard, Flood, Weak drought, or Strong drought); %Cst: change from base scenario, standard conditions; Pop: median population; CV: coefficient of variation. Entries are ordered by decreasing %Cco

Conditions	***Scenario***	***%Cco***	***%Cst***	***Pop***	***CV***
Flood	No wetland management in easements & flood	-33	-19	138600	0.22
Flood	No easements & flood	-38.5	-25.7	127200	0.24
Standard	No wetland management in easements	-68.8	-68.8	53300	0.50
Standard	No easements	-76.7	-76.7	39950	0.43
Weak Drought	No wetland management in easements & weak drought	-70.5	-72.5	47050	0.59
Weak Drought	No easements & weak drought	-80.9	-82.2	30400	0.57
Strong Drought	No wetland management in easements & strong drought	-12	-99.3	1100	0.96
Strong Drought	No easements & strong drought	-28	-99.5	900	1.08

Figure V.1 Simulation results in the absence of management in easements in the Mississippi Alluvial Valley (MAV) mallard model – overview. Note that y-axis scale varies between plots.

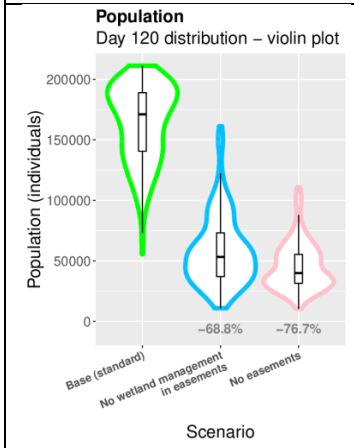
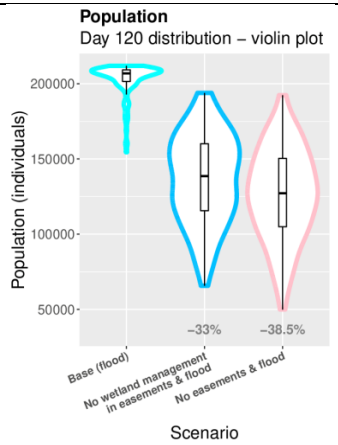
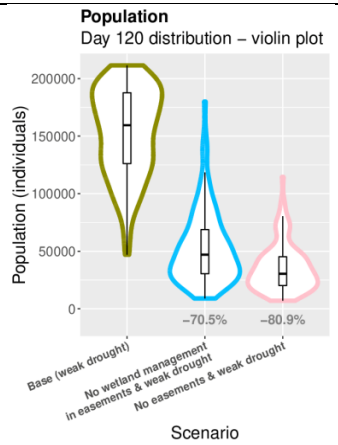
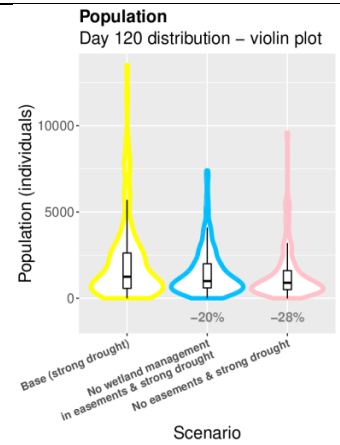
Standard conditions	Flood conditions	Weak drought conditions	Strong drought conditions
largest population at end of season: ***Base (standard)***	largest population at end of season: ***Base (flood)***	largest population at end of season: ***Base (weak drought)***	largest population at end of season: ***Base (strong drought)***
			

Figure V.2 Simulation results in the absence of management in easements in the Mississippi Alluvial Valley (MAV) mallard model - **Standard** environmental conditions. The shaded areas represent bilateral 95% value ranges.

Scenarios: ● ***No wetland management in easements*** ● ***No easements*** ● *Base (standard)*

Largest population at end of season, under standard conditions: ***Base (standard)***

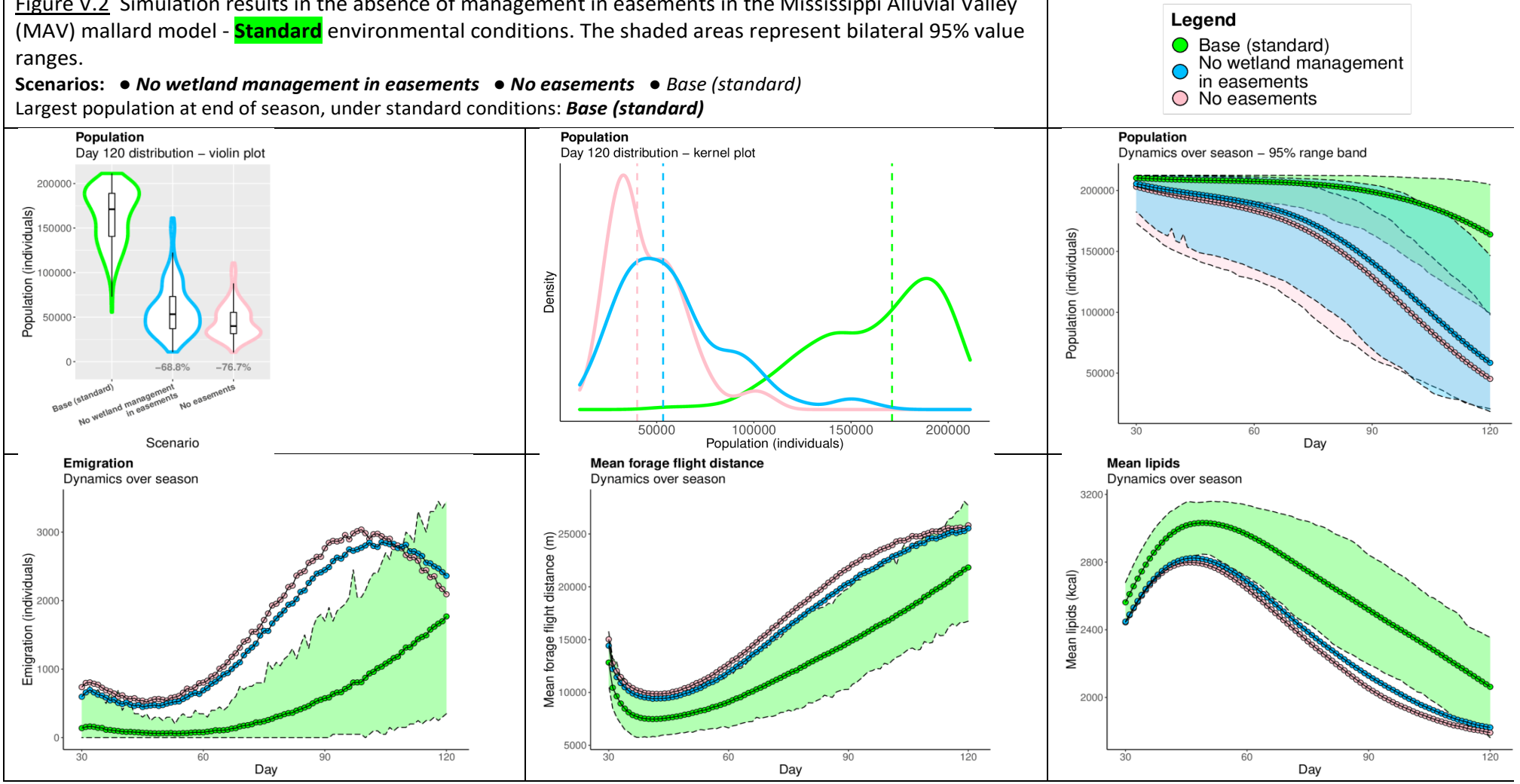


Figure V.3 Simulation results in the absence of management in easements in the Mississippi Alluvial Valley (MAV) mallard model – **Flood** conditions. The shaded areas represent bilateral 95% value ranges.
Scenarios: ● ***No wetland management in easements & flood*** ● ***No easements & flood*** ● *Base (flood)*
Largest population at end of season, under flood conditions: ***Base (flood)***

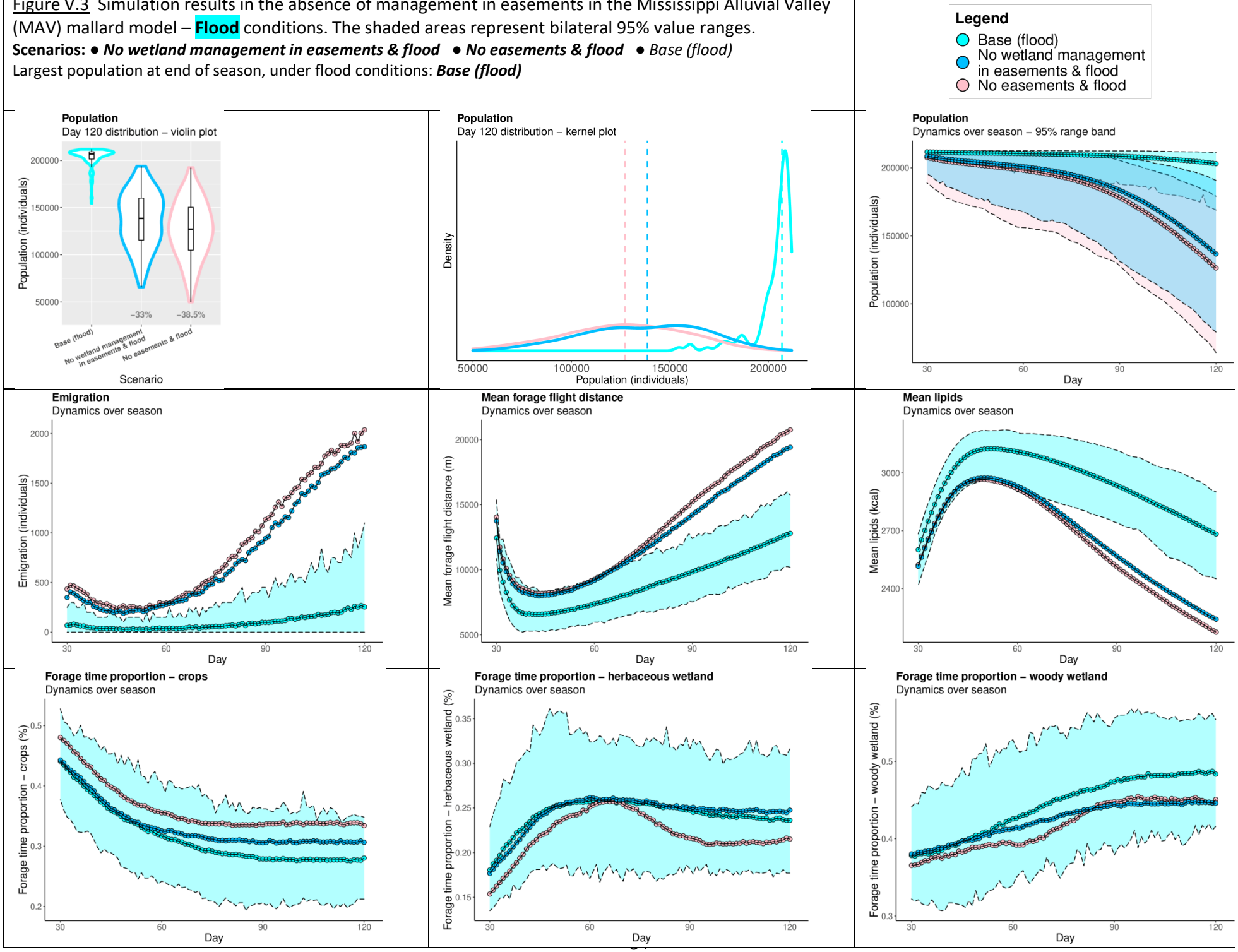


Figure V.4 Simulation results in the absence of management in easements in the Mississippi Alluvial Valley (MAV) mallard model - **Weak drought** conditions. The shaded areas represent bilateral 95% value ranges.

Scenarios: ● ***No wetland management in easements & weak drought*** ● ***No easements & weak drought*** ● *Base (weak drought)*

Largest population at end of season, under weak drought conditions: ***Base (weak drought)***

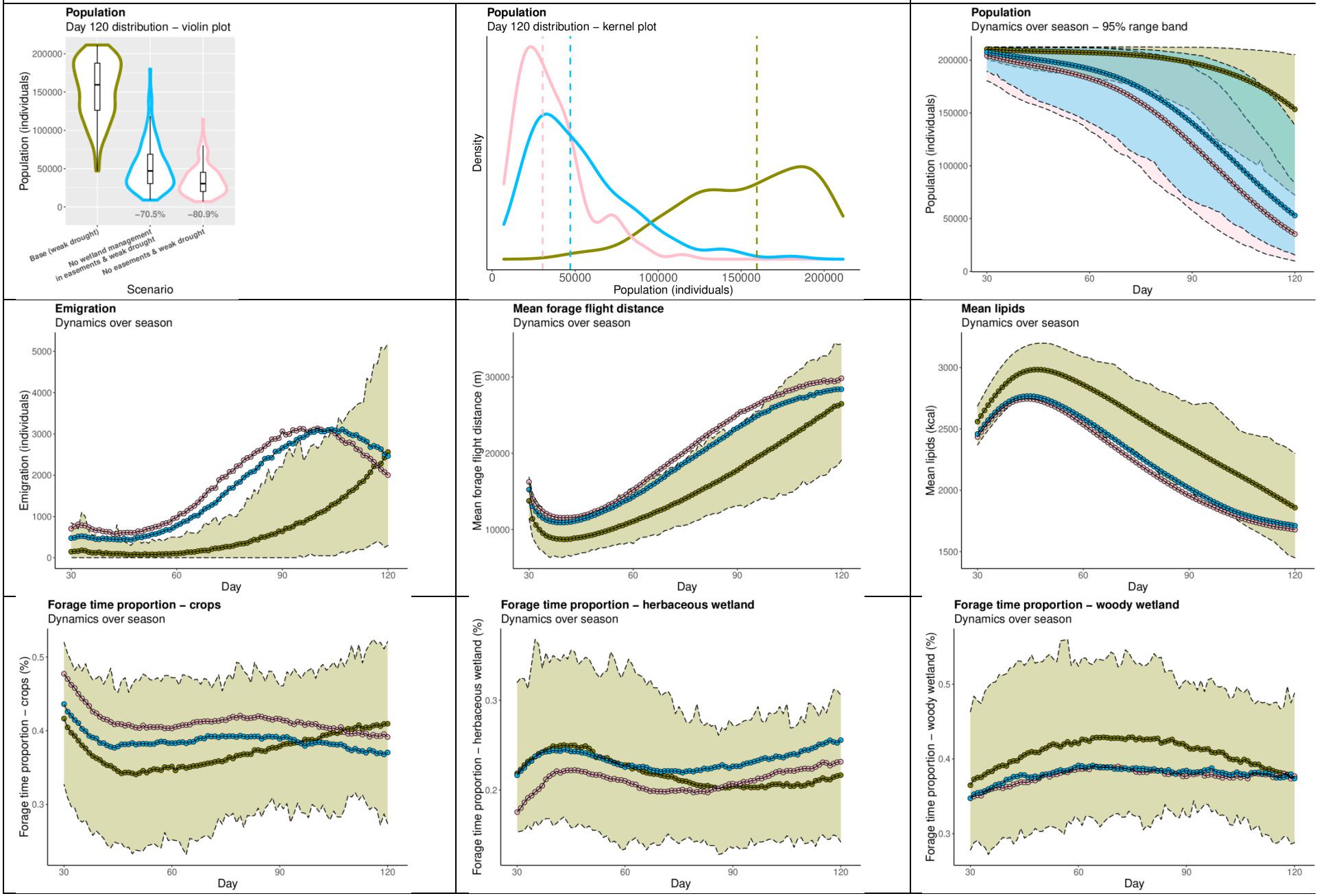
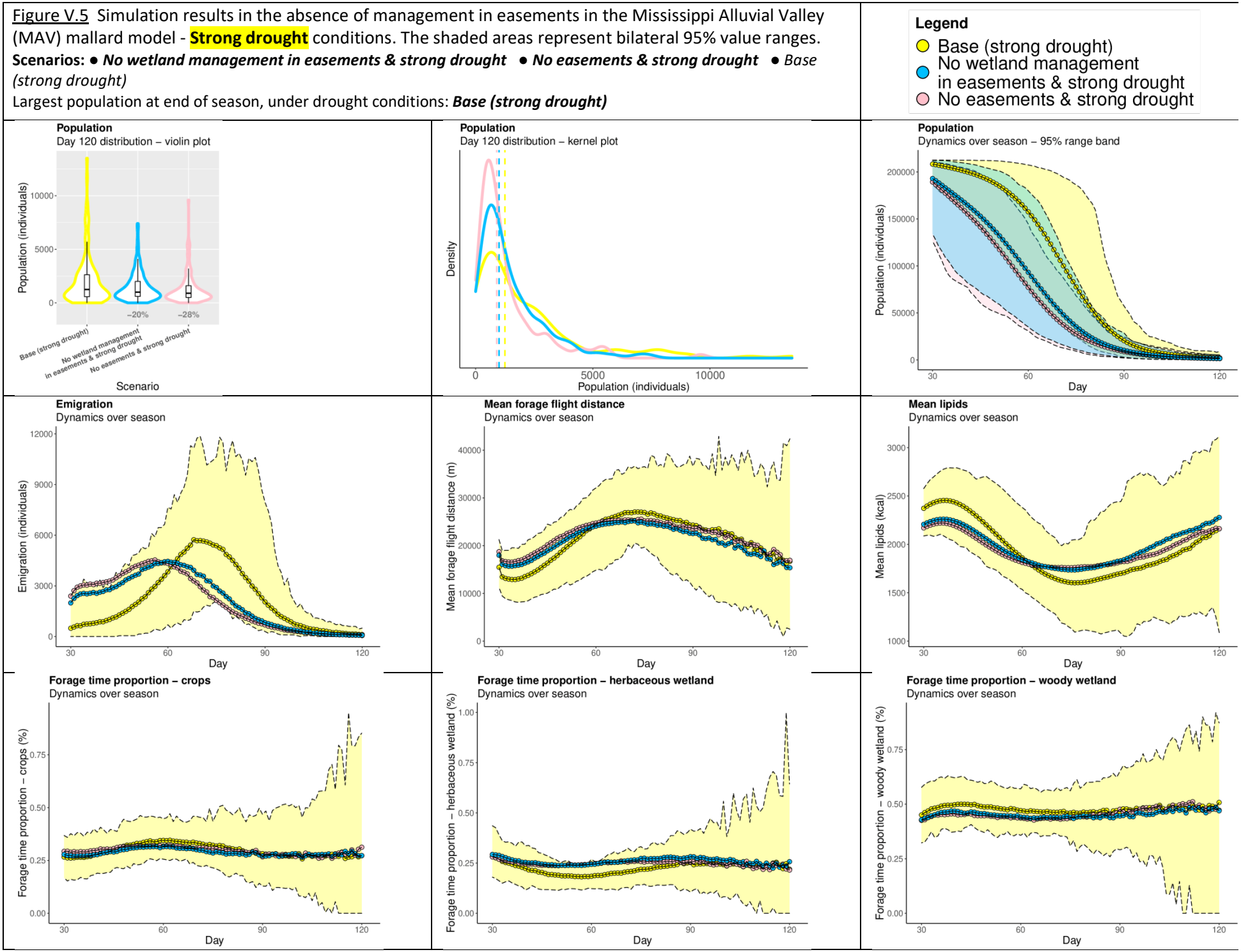


Figure V.5 Simulation results in the absence of management in easements in the Mississippi Alluvial Valley (MAV) mallard model - **Strong drought** conditions. The shaded areas represent bilateral 95% value ranges.

Scenarios: ● ***No wetland management in easements & strong drought*** ● ***No easements & strong drought*** ● *Base (strong drought)*

Largest population at end of season, under drought conditions: ***Base (strong drought)***



The conversion from managed to unmanaged herbaceous wetlands involved a reduction in food biomass by ~45%, that from restored herbaceous wetland to (random) crop resulted in a reduction by ~80%. Food energy values per gram are essentially identical among herbaceous wetland types, while the conversion to crops yields a ~25% increase in energy per gram. However, the massive reduction in biomass dominated these conversions, leading to a substantial decrease in food energy although the affected areas made up only a small fraction of the total foraging area (Table V.2). This was mostly caused by the loss of the abundant reservoirs of food biomass in managed wetlands, which together with rice crops constituted the most important late-season foraging sources.

Table V.2. Manipulated foraging area, percentage of total foraging area affected, and energy lost from/added to map, for each scenario in scenario group A of the Mississippi Alluvial Valley (MAV) mallard model.

Scenario	***Manipulated area***	***Percentage of total foraging area affected***	***Energy lost from map relative to Base (standard) (kcal)***
No wetland management in easements	All managed easement herbaceous wetlands	0.6%	-1.14×10^9
No easements	All managed or restored easement wetlands	1.2%	-2.56×10^9

Under all but strong drought conditions, the absence of managed and/or restored herbaceous wetlands led to an increased reliance on crops throughout the season. A concurrent increase in forage flight distances was caused by more rapidly depleted food on the landscape and the fact that crops tend to be further away from wetland roosting sites. In common with the results from various management scenarios (see Results C–E), the absence or presence of wetland management was of little consequence under conditions of strong drought.

It must be noted that the relative effect of the scenarios in the simulation is exaggerated because the model imposes the low-carrying-capacity landscape condition as something that suddenly happens at the beginning of the season, whereas the number of incoming ducks throughout November still reflects a high-carrying-capacity landscape. The result is rapid overexploitation of food resources. Unlike drought conditions, which may take effect from one year to the next, in reality these management-induced scarcity conditions would be of longer standing and fewer ducks would likely choose to immigrate. Thus, a smaller starting population would forage on the map and experience fewer effects of overcrowding, leading to proportionally lower losses in end-of-season populations. Regardless, in common environmental conditions, the final populations under these circumstances are unlikely to be larger than 50% of those found in the presence of easements and easement management. These scenarios illustrate that substantial additional mallard populations that would otherwise be absent are sustained in the modeled area under current management conditions.

B) Increasing the easement area (+25%, new easements or roundout) – random locations

In these scenarios, the area of foraging habitat contained in easements was increased by a total of ~25% of the existing easement area (+ ~154 km^2). This is done by either establishing new, unconnected easements (**new easements**), or by increasing the contiguous area of existing easements (**roundout**). In either method, new foraging patches were added until a total increase of ~154 km^2 was achieved. All new easement patches received a minimum flooding probability of 25%, and affected crop patches were converted to restored wetlands. Patches were added either in **small units** (new easements: created easements were of size ~equal to the median size of existing easements; roundout: all patches directly contiguous to the starting easement were added) or in **large units** (new easements: created easements were of size ~equal to the 3rd quartile size of existing easements; roundout: a second layer of contiguous patches was added). In any case, placement on the map was **random** (new easements: random new locations; roundout: random starting easements).

Outcomes: (compared to **condition base**)

Under standard conditions, scenarios yielded population gains at end of season of 3.2–10.2%. **New easements (large units)** had the largest population [+10.2%; +17,500 mallards].

Under flood conditions, scenarios yielded gains of 0.5–0.9%. **New easements (small units)** had the largest gain [+0.9%; +1,850 mallards].

Under weak drought conditions, scenarios yielded gains of 2.1–6.1%. **New easements (large units)** had the largest gain [+16.2%; +25,800 mallards].

Under strong drought conditions, scenarios yielded a change of -4–44% (but small absolute numbers). **Roundout (large units)** had the largest gain [+44%; +550 mallards].

Table V.3. Metrics of total population at end of season (day 120) in the Mississippi Alluvial Valley (MAV) mallard model, for scenario group B. %Cco: % change from condition base (base scenario under relevant environmental conditions: Standard, Flood, Weak drought, or Strong drought); %Cst: change from base scenario, standard conditions; Pop: median population; CV: coefficient of variation. Entries are ordered by decreasing %Cco

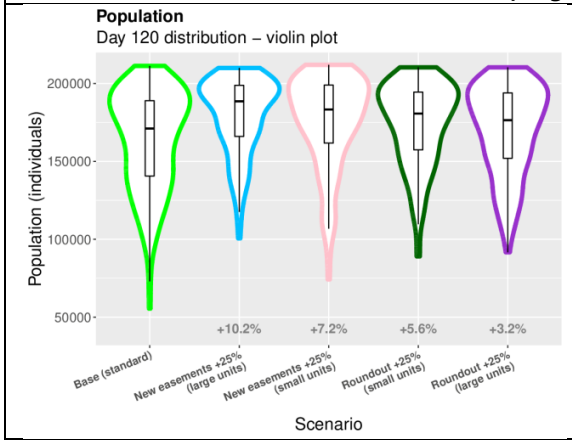
Conditions	*Scenario*	*%Cco*	*%Cst*	*Pop*	*CV*
Flood	New easements +25% (small units)	0.9	22	208750	0.05
Flood	New easements +25% (large units	0.8	21.9	208600	0.03
Flood	Roundout +25% (small units)	0.5	21.6	208000	0.04
Flood	Roundout +25% (large units)	0.5	21.5	207850	0.04
Standard	New easements +25% (large units)	10.2	10.2	188600	0.14
Standard	New easements +25% (small units)	7.2	7.2	183350	0.17
Standard	Roundout +25% (small units)	5.6	5.6	180700	0.15
Standard	Roundout +25% (large units)	3.2	3.2	176500	0.17
Weak Drought	New easements +25% (large units)	16.2	8.3	185250	0.20
Weak Drought	New easements +25% (small units)	9	1.6	173800	0.21
Weak Drought	Roundout +25% (small units)	5.5	-1.7	168150	0.15

Table V.3. continued.

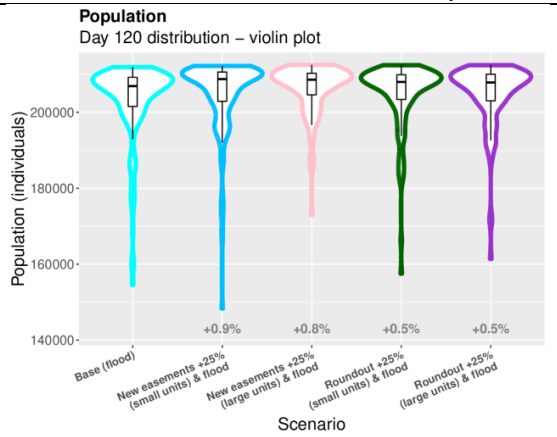
Conditions	***Scenario***	***%Cco***	***%Cst***	***Pop***	***CV***
Weak Drought	Roundout +25% (large units)	2.1	-4.9	162750	0.25
Strong Drought	Roundout +25% (large units)	44	-98.9	1800	0.89
Strong Drought	Roundout +25% (small units)	28	-99.1	1600	1.16
Strong Drought	New easements +25% (small units)	20	-99.1	1500	0.87
Strong Drought	New easements +25% (large units)	-4	-99.3	1200	1.04

Figure V.6 Simulation results when increasing the easement area (+25%, new easements or roundout) at random locations in the Mississippi Alluvial Valley (MAV) mallard model – overview. Note that y-axis scale varies between plots.

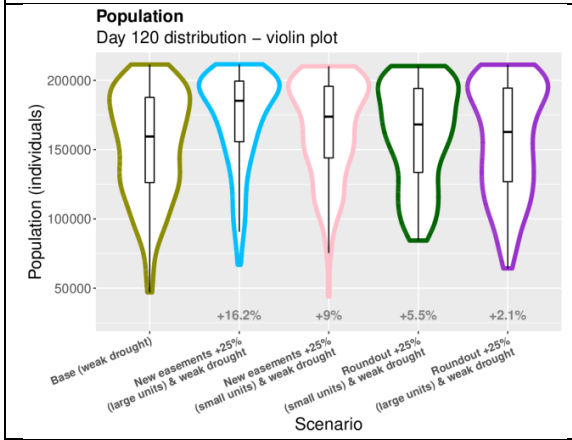
Standard conditions largest population at end of season:
New easements (large units) [Base +10.2%]



Flood conditions largest population at end of season:
New easements (small units) [Flood +0.9%]



Weak drought conditions largest population at end of season:
New easements (large units) [Weak drought +16.2%]



Strong drought conditions largest population at end of season:
Roundout (large units) [Strong drought +44%]

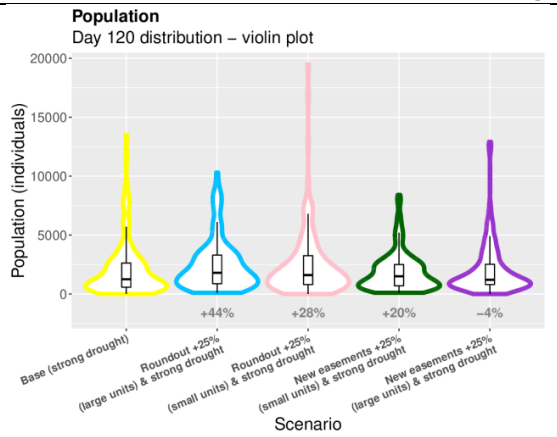


Figure V.7 Simulation results when increasing the easement area (+25%, new easements or roundout) at random locations in the Mississippi Alluvial Valley (MAV) mallard model - **Standard** environmental conditions. The shaded areas represent bilateral 95% value ranges.

Scenarios: ● ***New easements (large units)*** ● ***New easements (small units)*** ● ***Roundout (large units)*** ● ***Roundout (small units)*** ● *Base (standard)*

Largest population at end of season, under standard conditions: ***New easements (large units)*** [Base +10.2%]

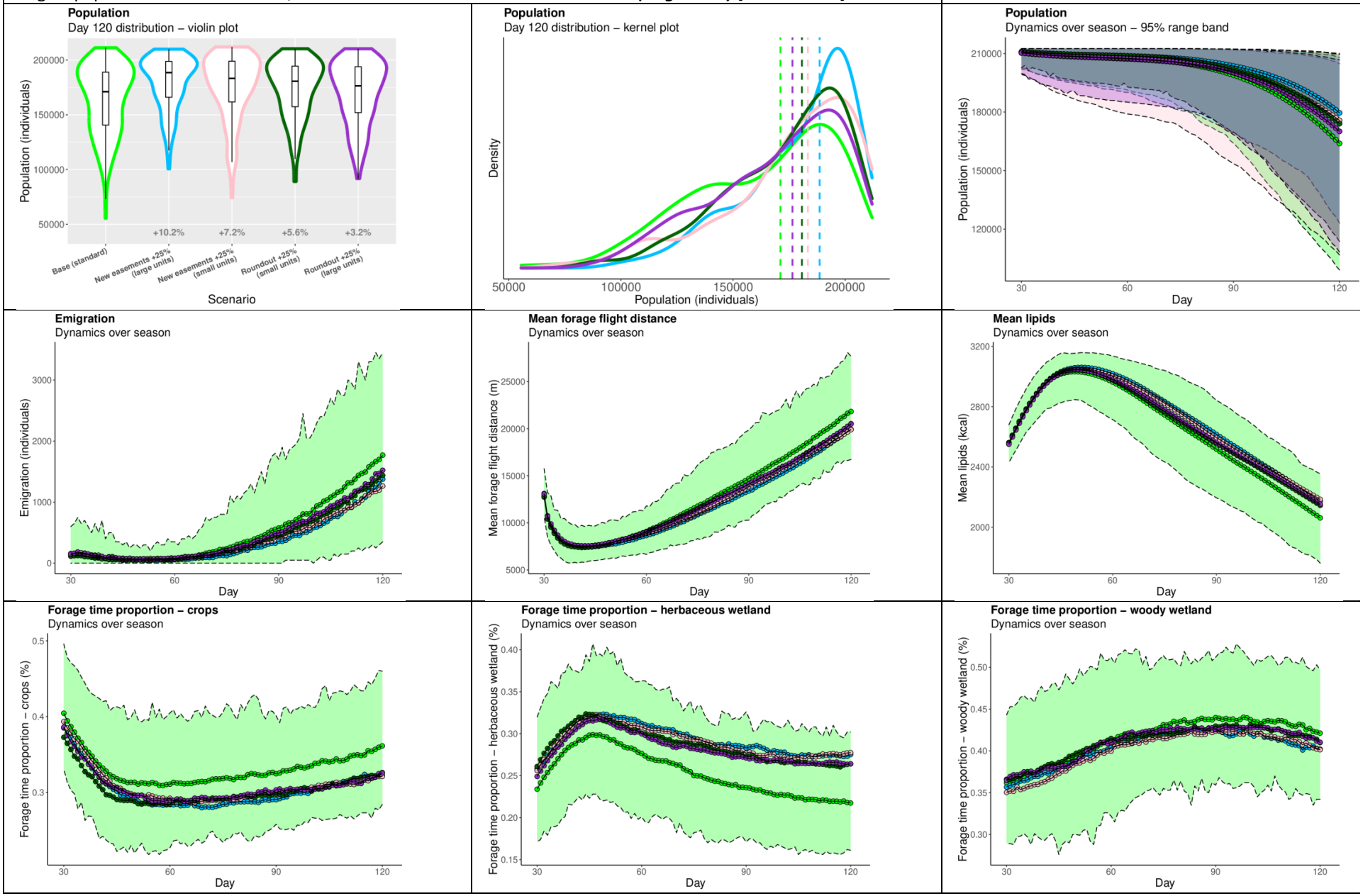
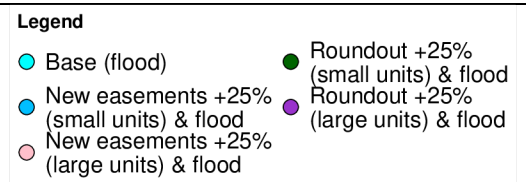
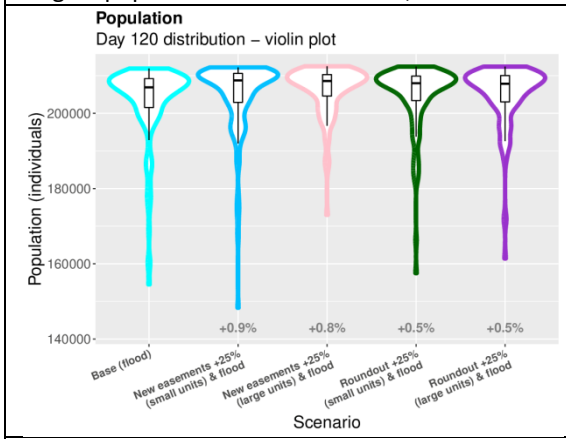


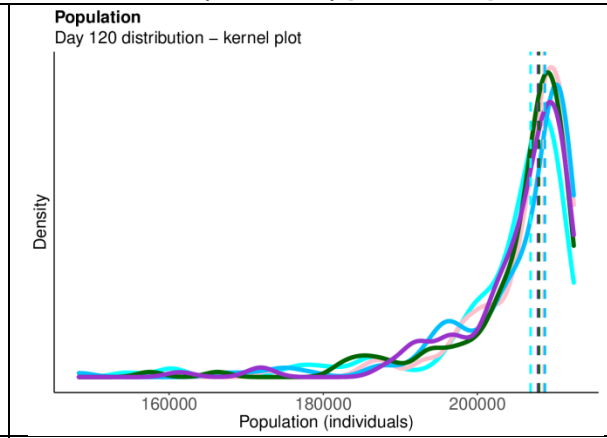
Figure V.8 Simulation results when increasing the easement area (+25%, new easements or roundout) at random locations in the Mississippi Alluvial Valley (MAV) mallard model - **Flood** conditions. The shaded areas represent bilateral 95% value ranges.

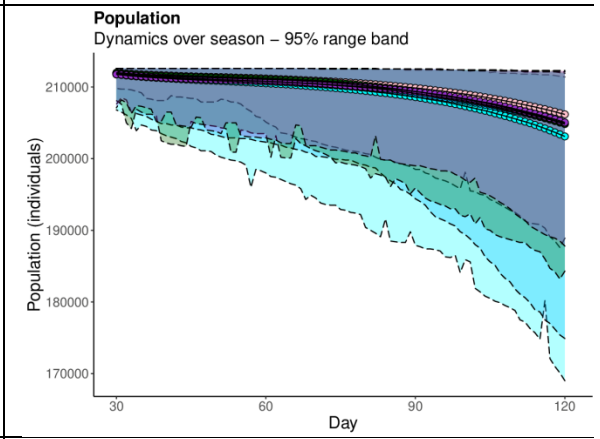
Scenarios: ***{ ● New easements (large units) ● New easements (small units) ● Roundout (large units) ● Roundout (small units) } & flood*** ● *Base (flood)*

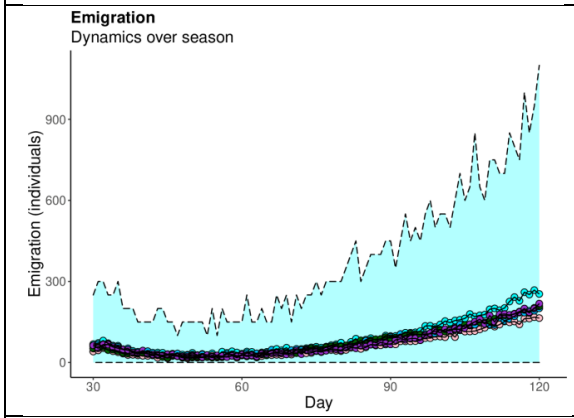
Largest population at end of season, under flood conditions: ***New easements (small units)*** [Flood +0.9%]

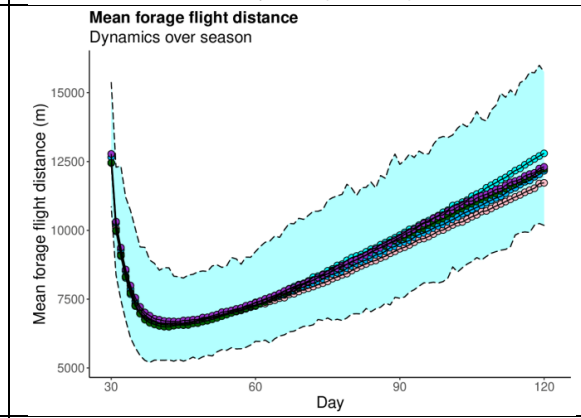


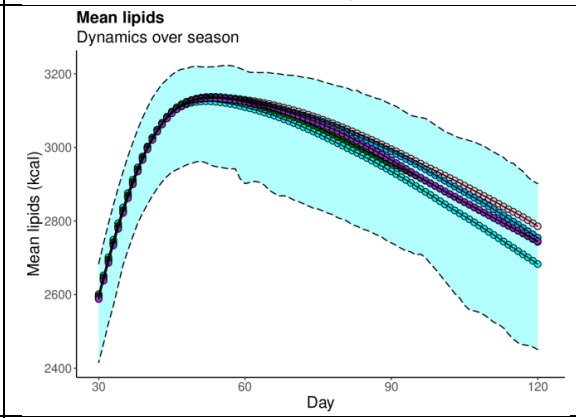


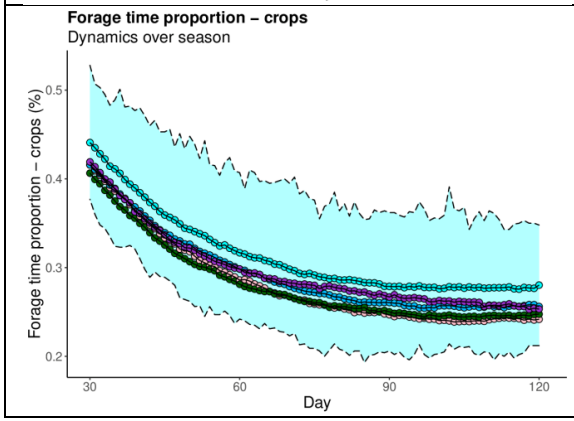


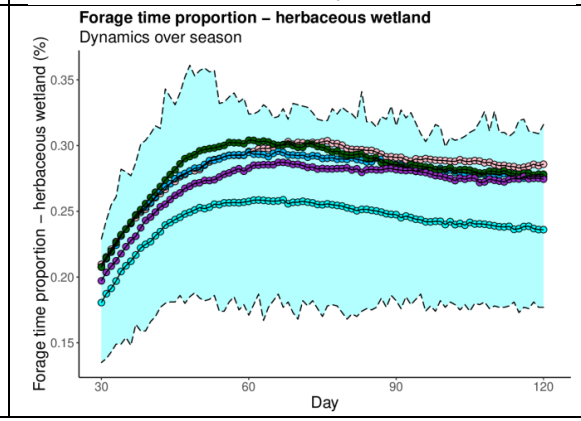












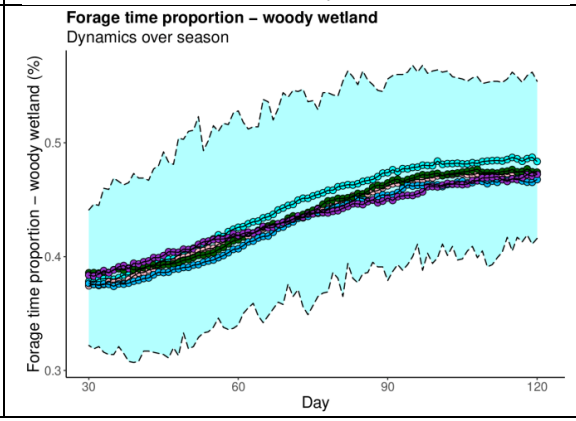


Figure V.9 Simulation results when increasing the easement area (+25%, new easements or roundout) at random locations in the Mississippi Alluvial Valley (MAV) mallard model - **Weak drought** conditions. The shaded areas represent bilateral 95% value ranges.

Scenarios: ***{ ● New easements (large units) ● New easements (small units) ● Roundout (large units) ● Roundout (small units) } & weak drought*** ● *Base (weak drought)*

Largest pop. at end of season, wk. drought conditions: ***New easements (large units)*** [Weak drought +16.2%]

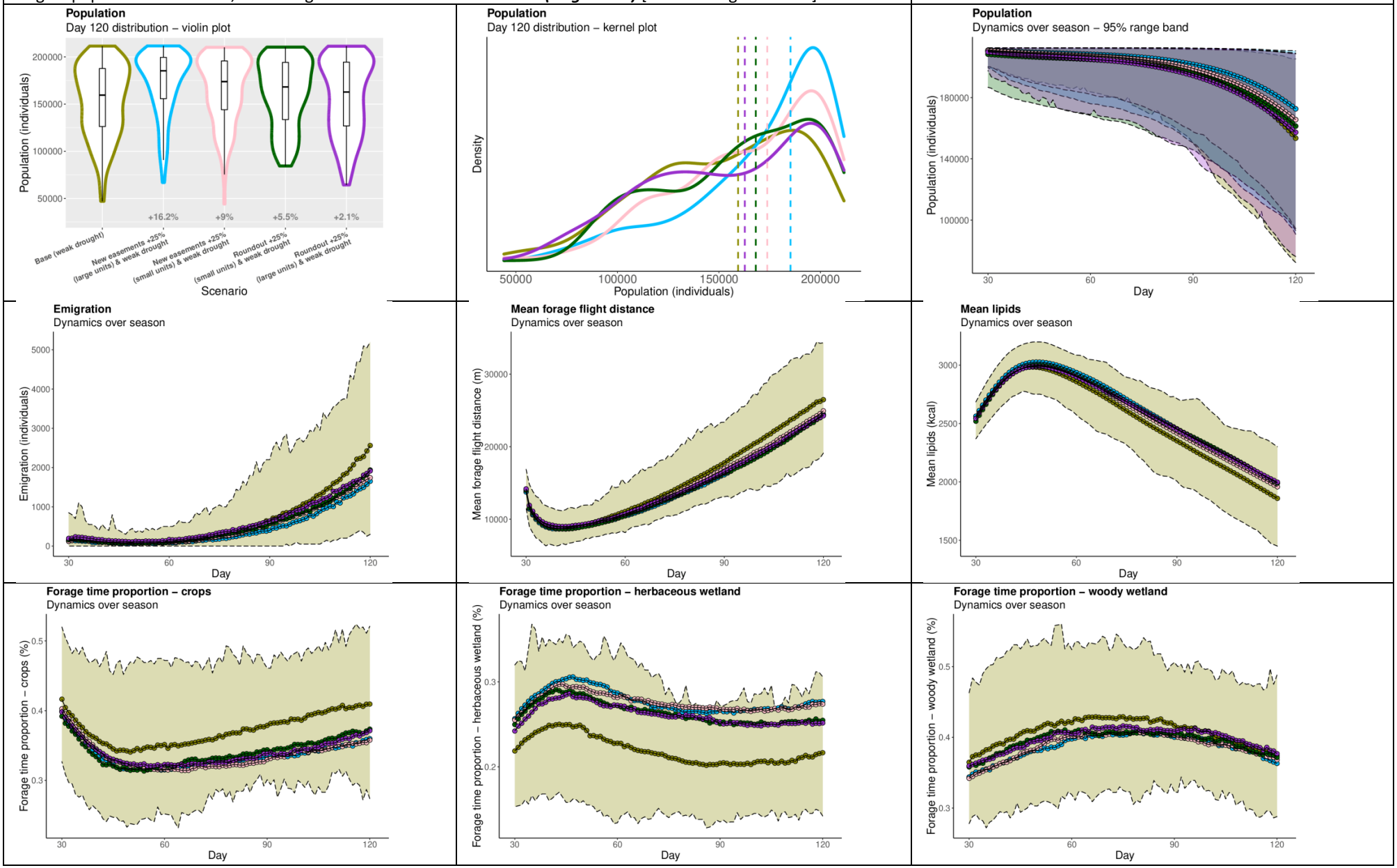
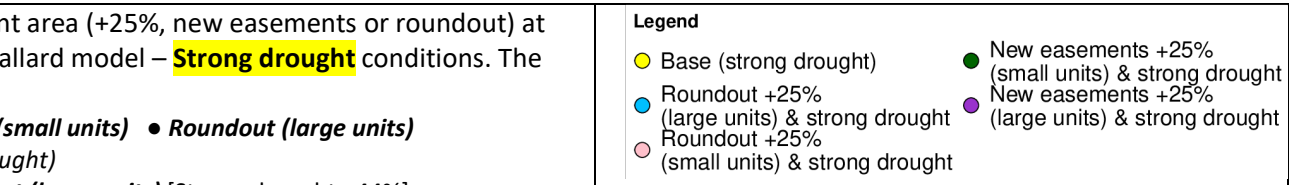
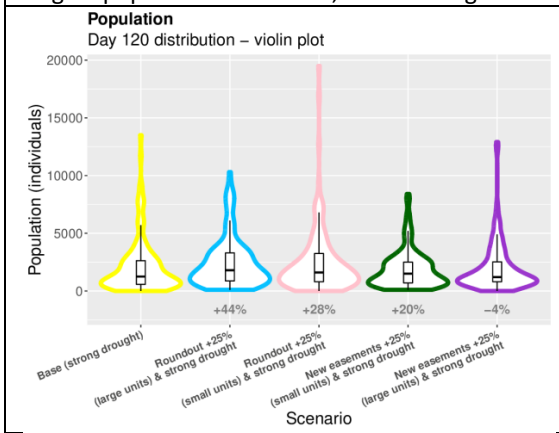


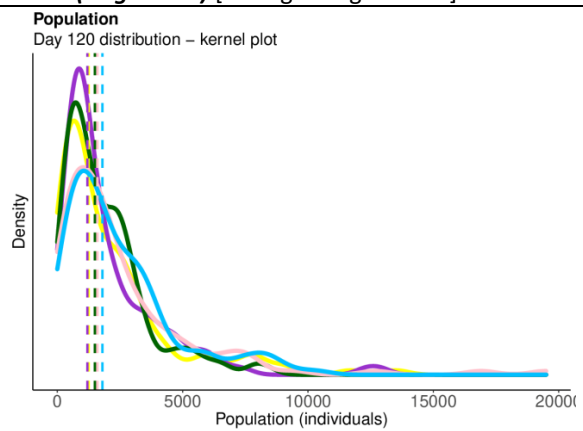
Figure V.10 Simulation results when increasing the easement area (+25%, new easements or roundout) at random locations in the Mississippi Alluvial Valley (MAV) mallard model – **Strong drought** conditions. The shaded areas represent bilateral 95% value ranges.

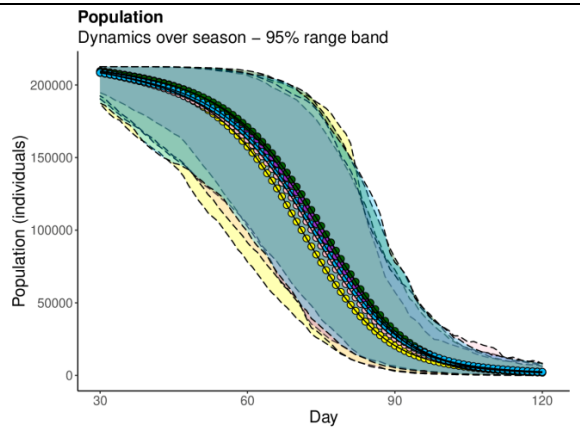
Scenarios: ***{ ● New easements (large units) ● New easements (small units) ● Roundout (large units) ● Roundout (small units) } & strong drought*** ● *Base (strong drought)*

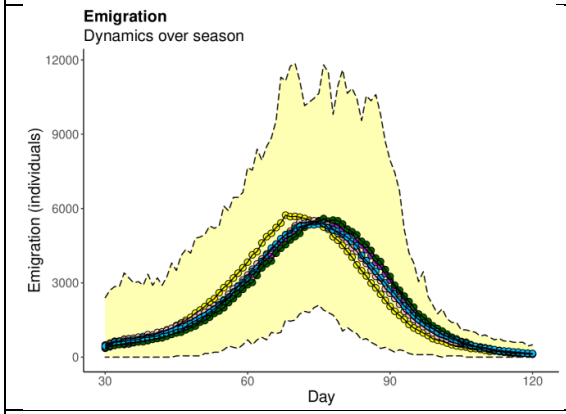
Largest pop. at end of season, under drought conditions: ***Roundout (large units)*** [Strong drought +44%]

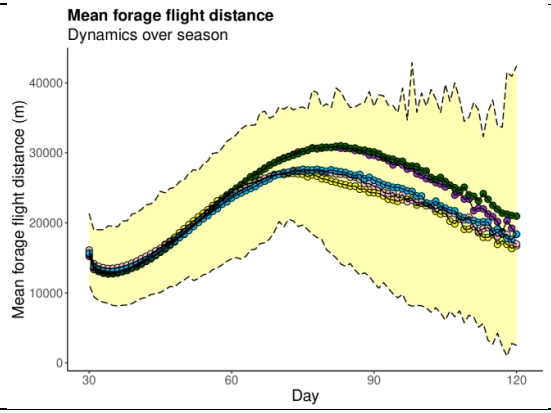


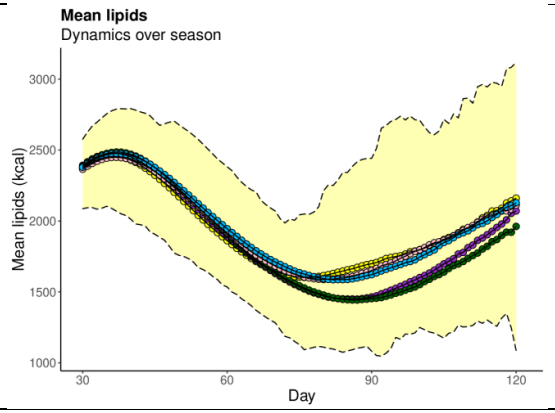


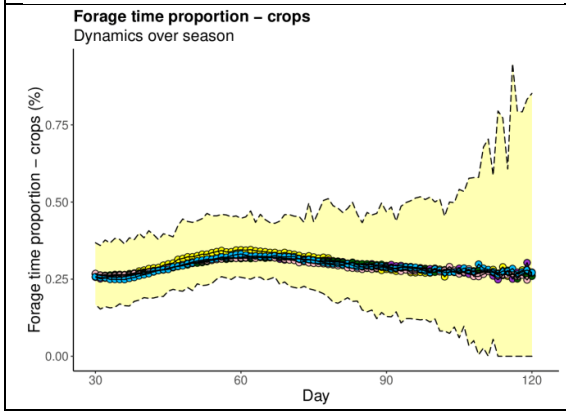


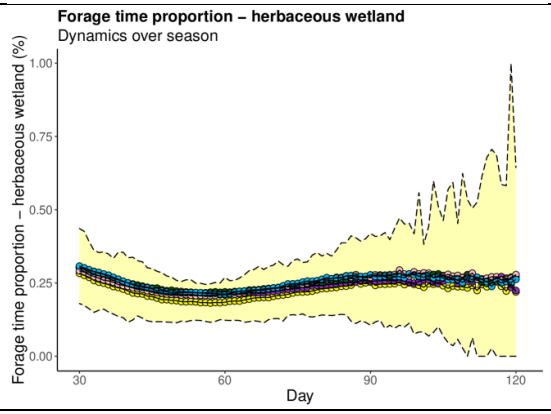


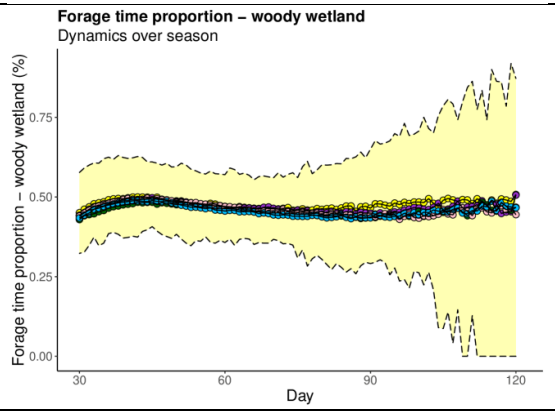












The randomly placed addition of new easement area equal to 25% of the existing easement area had a substantial effect under standard and weak drought conditions. The most effective scenarios under these two conditions increased end-of-season population by 10.2% (17,500 mallards) and 16.2% (25,800 mallards), respectively, over the condition base. Under the more extreme flood or strong drought conditions, gains were much smaller with outcomes in the 550–1,850 mallards range. Variability in top scenario outcomes increased from standard (CV 0.16) to weak drought (CV 0.22) to flood (CV 0.4) to strong drought conditions (0.89) (Figure V.6, Table V.3).

The main impact of these scenarios was to increase the availability of herbaceous wetlands by converting affected crop patches to higher-yield restored herbaceous wetlands (an increase in mean biomass from 5.5–9.6 g/m^2 to 33.1 g/m^2); thus the gain in herbaceous wetlands came at the expense of available crop forage. These habitat type changes varied between scenario types. New easement scenarios were set up such that newly inducted patches were composed of ~69% of convertible crops and ~31% of pre-existing wetlands. In contrast, in roundout scenarios, contiguous patches were not proportionally filtered for habitat type, resulting in a lower convertible crops proportion of ~38% (see Methods III C). Food energy gain in the landscape corresponded to this and was larger for new easements than for roundouts (Table V.3). Conversion affected 0.6–1.1% of the total foraging area, and resulted in a strong shift in habitat use away from crops to herbaceous wetland in all conditions (Figure V.6–10). As a secondary change, all newly restored wetland patches added to easements had their flooding probabilities increased to a minimum of 25% (under the assumption that such wetlands would not be permanently dried out); this had no noticeable effect on overall flooding probability but ensured that newly added wetlands would play a functional role in at least 25% of replicates under standard conditions.

Table V.3. Manipulated foraging area, percentage of total foraging area affected, percentage of total foraging area that was converted from crops to restored wetland, and energy added to map, for each scenario in scenario group B of the Mississippi Alluvial Valley (MAV) mallard model.

Scenario	***Manipulated area***	***Percentage of total foraging area affected***	***Percentage of total foraging area converted from crops to restored wetland***	***Energy added to map relative to Base (standard) (kcal)***
New easements +25% (large units)	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	1.1%	2.03×10^9
New easements +25% (small units)	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	1.1%	2.1×10^9
Roundout +25% (large units)	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	0.6%	1.49×10^9
Roundout +25% (small units)	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	0.6%	1.55×10^9

Under standard conditions (Figure V.7), addition of large new easements was most effective in increasing mallard abundance (+10.2%). While all candidate scenarios had a wide range of possible outcomes, this scenario had a greater proportion of outcomes shifted towards high population numbers. Addition of small new easements was noticeably less effective (+7.2%), while

the small unit roundout scenario achieved only approximately half the gain of the top scenario (+5.6%), and large unit roundout had the least effect (+3.2%). The scenarios showed little difference in emigration from the map, forage flight distance, stored lipids, or forage area usage. All scenarios had a greater than base use of herbaceous wetland at the expense of crop use, as expected.

The same ranking and dynamics held under weak drought conditions (Figure V.9); however, differences in end-of-season population were more pronounced, with large new easements achieving +16.2% increase, while large unit roundouts yielded only +2.1%. Under flood conditions (Figure V.8), the same general ranking held but gains in median population outcome from enhancement scenarios became small (950–1,850 mallards) and within-group differences diminished. Under strong drought conditions (Figure V.10), gains in population size over the condition base were minimal (250–550 mallards; *note that % change vs condition base is high due to small absolute magnitude*), as were differences between scenarios. The small resultant differences favored roundouts over new easements, presumably because the energetic expense of longer flight distances was a more substantial drain on already energetically-stressed birds. Overall, under unusually high- or low-flooded conditions, the availability of additional high-forage herbaceous wetlands did not matter much because they either constituted an insignificant addition to the large available foraging habitat (flood) or because most of them were rendered inaccessible through lack of flooding (strong drought).

The main difference in the tested scenarios' effectiveness on mallard population retention clearly rested on the larger area of restored wetlands (and smaller area of pre-existing wetlands) added to easements in the new easement scenarios, as opposed to the roundout scenarios, and, consequently, greater addition of food energy. A secondary effect was the replacement of the fast-decaying crops (see Figure IV.5 and accompanying text) with wetland food reservoirs of greater longevity. Among the two new easement scenarios, the greater yield of the large unit variant as compared to the small unit variant suggests a substantial benefit derived from the establishment of fewer, larger cohesive feeding areas that allow for efficient foraging without frequent relocations. Note that contiguousness was even greater for the roundout scenarios, which added on to existing easement areas; but this was not enough to offset the comparative lack in energy gain. Thus, it appears that absolute gain in food resources was the main driver in ranking these scenarios, modified by connectivity considerations.

A subtle difference between new easement and roundout scenarios was their interaction with refuges, which provided roosting locations. Two thirds of refuges were located in sanctuary areas, which tended to be close to existing easements. Thus, roundout scenarios tended to add new easement patches close to roosting locations, which reduced flight distances; while new easement scenarios added patches that were widely dispersed over the map, but tended to be relatively far from refuges. This difference was not obvious under standard or weak drought conditions, but became apparent under strong drought conditions (Figure V.10, mean forage flight distance). However, the scattered new easement pattern may have also opened up new areas of the map for foraging by drawing mallards to little-exploited locations among croplands, while the more concentrated roundout pattern may have tended to constrain agents to the main easement/sanctuary areas with their high percentage of low-yield woody wetlands. This possible tradeoff is difficult to quantify from the model outputs, but may point to the importance of establishing foraging areas where limited wetland foraging opportunities exist.

In summary, under standard or weak drought conditions, the opportunistic addition of larger new easement patches (here represented as random) was effective in substantially increasing end-of-season population numbers. The best results came from newly established and unconnected easements, established in larger units, which may have provided the best combination of crop area converted to higher-yield wetlands, foraging unit cohesiveness, and possibly access to formerly little exploited map areas. Under unusually flooded or severe drought conditions, gains were much smaller and none of the tested scenarios performed conspicuously better than the others.

C) Increasing the easement area (+25%, new easements or roundout) – selected locations

In these scenarios, as in approach B) (see above), the area of foraging habitat contained in easements was increased by 25% of the existing easement area (+ 154 km^2), in the form of either **new easements** or by **roundout,** in **large** or **small units**. In contrast to B), these scenarios included not only variants with random placement of expansion locations, but also scenarios with **location selection**. The first option was placement within a 15-km buffer **close to sanctuaries**, assuming benefits from proximity to these disturbance-free areas with many roost sites. The second option was the use of only foraging patches that were present in the NWI database, assuming benefits from restoring crop patches that historically were wetlands. These scenarios were only tested under standard conditions (no flood, weak drought, or strong drought variants) to reduce required simulation time.

Outcomes: (compared to **condition base**)

Under standard conditions, scenarios yielded population gains at end of season of 3.2–10.2%. **New easements (large units)** *(random placement)* had the largest population [+10.2%; +17,500 mallards].

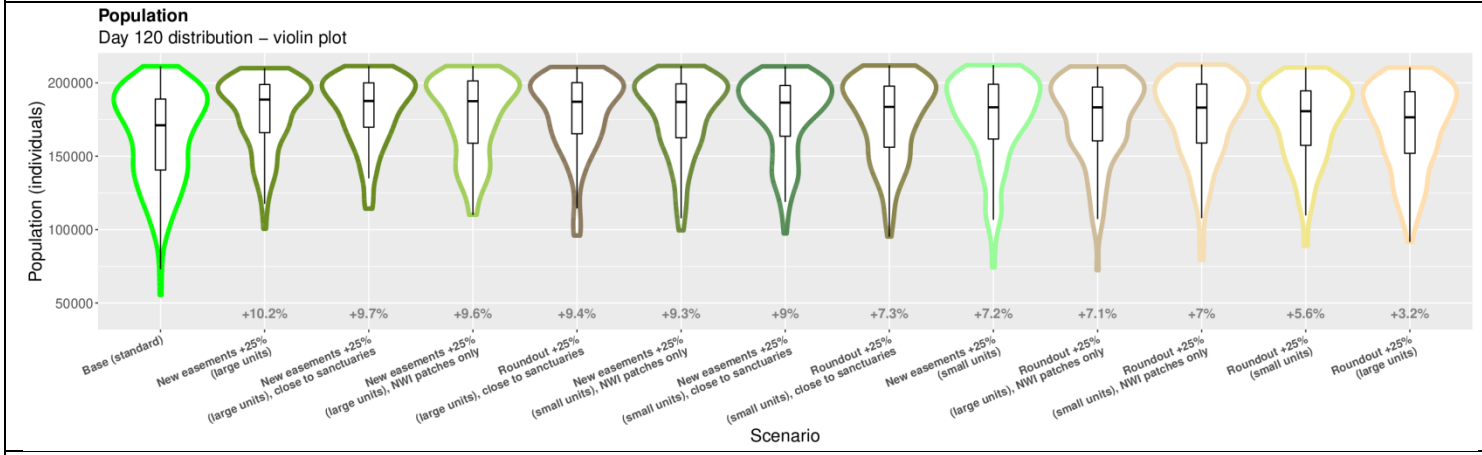
Table V.4. Metrics of total population at end of season (day 120) in the Mississippi Alluvial Valley (MAV) mallard model, for scenario group C. %Cco: % change from condition base (base scenario under relevant environmental conditions: Standard, Flood, Weak drought, or Strong drought); %Cst: change from base scenario, standard conditions; Pop: median population; CV: coefficient of variation. Entries are ordered by decreasing %Cco. NWI is National Wetlands Inventory.

Conditions	***Scenario***	***%Cco***	***%Cst***	***Pop***	***CV***
Standard	New easements +25% (large units), random placement	10.2	10.2	188600	0.14
Standard	New easements +25% (large units), close to sanctuaries	9.7	9.7	187650	0.13
Standard	New easements +25% (large units), NWI patches only	9.6	9.6	187500	0.15
Standard	Roundout +25% (large units), close to sanctuaries	9.4	9.4	187150	0.14
Standard	New easements +25% (small units), NWI patches only	9.3	9.3	186950	0.15
Standard	New easements +25% (small units), close to sanctuaries	9	9	186500	0.15
Standard	Roundout +25% (small units), close to sanctuaries	7.3	7.3	183600	0.16
Standard	New easements +25% (small units), random placement	7.2	7.2	183350	0.17
Standard	Roundout +25% (large units), NWI patches only	7.1	7.1	183300	0.16
Standard	Roundout +25% (small units), NWI patches only	7	7	183150	0.16
Standard	Roundout +25% (small units), random placement	5.6	5.6	180700	0.15
Standard	Roundout +25% (large units), random placement	3.2	3.2	176500	0.17

Figure V.11 Simulation results when increasing the easement area (+25%, new easements or roundout) at selected locations in the Mississippi Alluvial Valley (MAV) mallard model - **Standard** environmental conditions. NWI is National Wetlands Inventory.

Scenarios: ***{ ● New easements (large units) ● New easements (small units) ● Roundout (large units) ● Roundout (small units) } ● { … } & close to sanctuaries ● { … } & NWI patches only*** ● *Base (standard)*

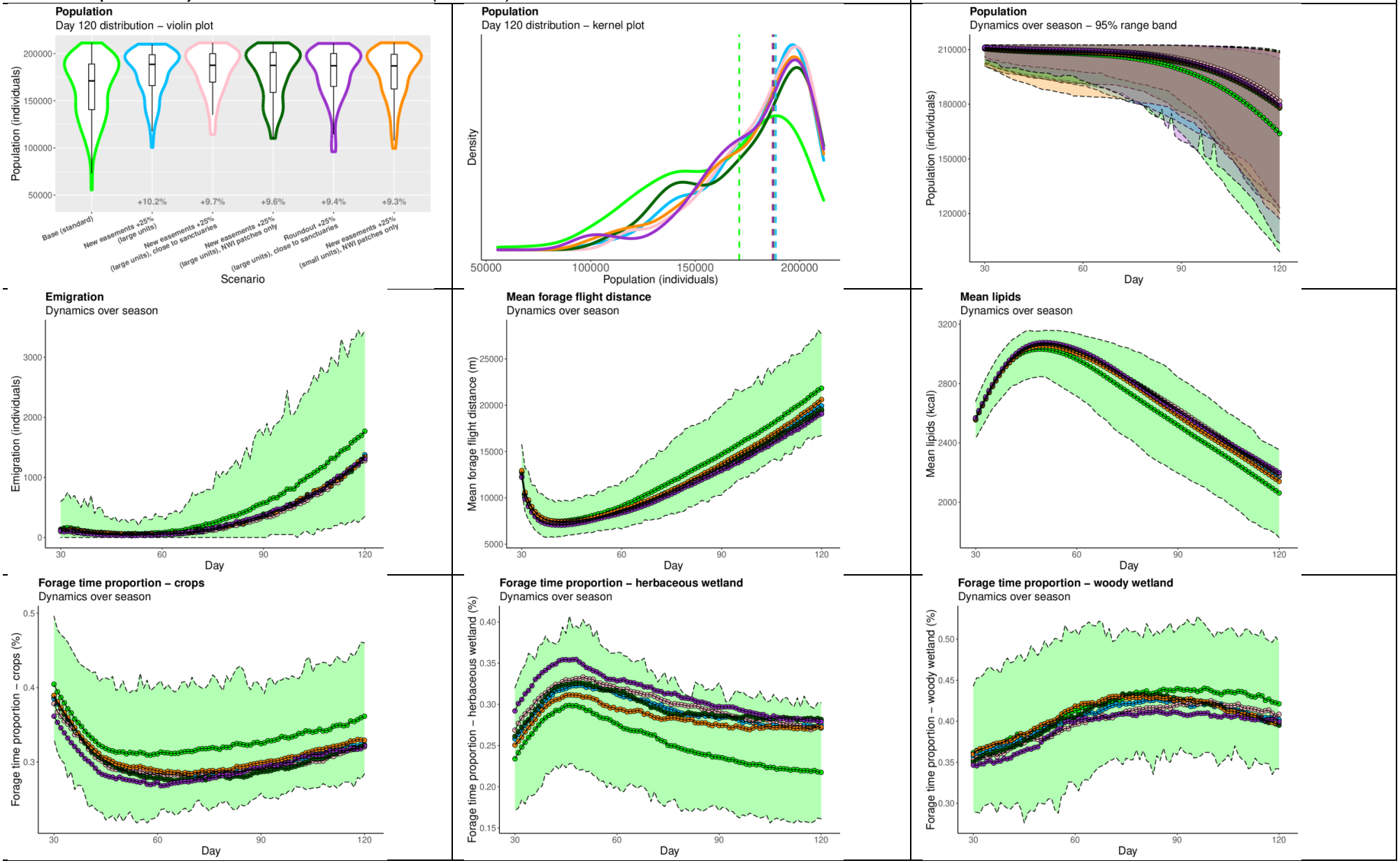
Largest population at end of season, under standard conditions: ***New easements (large units)*** [Base +10.2%]



To illustrate dynamics over the season, details for the **top five scenarios** are shown on the following page.

Figure V.12 Simulation results when increasing the easement area (+25%, new easements or roundout) at selected locations in the Mississippi Alluvial Valley (MAV) mallard model - **Standard** environmental conditions. The shaded areas represent bilateral 95% value ranges. NWI is National Wetlands Inventory.
Subset – showing the top 5 scenarios

Scenarios: ● ***New easements (large units)*** ● ***New easements (small units) & NWI patches only***
● ***Roundout (large units) & close to sanctuaries*** ● ***Roundout (large units) & NWI patches only***
● ***Roundout (small units) & close to sanctuaries*** ● *Base (standard)*



These scenarios were only tested under standard conditions to limit the number of time-intensive simulation runs. Based on the overall dynamics observed in the model, we assumed the applicability of the relationships between runs under different environmental conditions that were discussed in Results section B. That is, we assumed that for increased area scenarios, the ranking under weak drought conditions had few differences from standard conditions, and that under flood and strong drought conditions, differences in net gain between scenarios became small enough to make scenario ranking largely irrelevant.

The top scenario among area increase approaches was large new easements with random placement (+10.2%, +17,500 mallards), the best among random placement variants (see Results II B). This was followed closely by five other scenarios that differed by at most 2,100 mallards (a range of 1.2%). Among these similar top scenarios, there was only a single roundout scenario (large unit roundout, close to sanctuaries; +9.4%, +16,050 mallards), while all but one of the new easement scenarios were part of this group. All scenarios had a similar outcome variance (range of coefficient of variation (CV) differences of 0–0.03) and had a lower probability of instances of low or very low end-of-season populations than the base scenario.

These outcomes indicate that similar to the random placement scenarios, food energy gain in the landscape (following the amount of crops converted to restored wetlands) remained the most important driver of end-of-season population gains. This favored new easement scenarios over roundouts. Among the new easement scenarios, the selected location variants (close to sanctuaries, or on NWI patches) performed similarly to random placement. There was no consistent pattern in food energy gain (Table V.5) or ranking among the random, close to sanctuaries, or NWI patches variants. Additionally, the large unit variants yielded slightly better results than the small unit variants. Thus, for new easement placement, the two main determinants remained those discussed in the previous section (Results II B)—absolute energy gain and greater foraging area cohesiveness—while the factor of selective placement was largely unimportant. This added aspect neither improved outcomes noticeably, nor did the more restrictive placement requirements (and thus smaller pool of candidate locations) show detrimental effects.

Table V.5. Manipulated foraging area, percentage of total foraging area affected, percentage of total foraging area that was converted from crops to restored wetland, and energy added to map, for each scenario in scenario group C of the Mississippi Alluvial Valley (MAV) mallard model.

Scenario	***Manipulated foraging area***	***Percentage of total foraging area affected***	***Percentage of total foraging area converted from crops to restored wetland***	***Energy added to map relative to Base (standard) (kcal)***
New easements +25% (large units), random placement	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	1.1%	2.03×10^9
New easements +25% (large units), close to sanctuaries	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	1.1%	1.98×10^9
New easements +25% (large units), NWI patches only	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	1.2%	2.26×10^9
New easements +25% (small units), random placement	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	1.1%	2.1×10^9
New easements +25% (small units), close to sanctuaries	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	1.1%	1.96×10^9

New easements +25% (small units), NWI patches only	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	1.1%	1.99×10^9
Roundout +25% (large units), random placement	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	0.6%	1.49×10^9
Roundout +25% (large units), close to sanctuaries	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	0.7%	1.66×10^9
Roundout +25% (large units), NWI patches only	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	0.7%	1.63×10^9
Roundout +25% (small units), random placement	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	0.6%	1.55×10^9
Roundout +25% (small units), close to sanctuaries	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	0.6%	1.44×10^9
Roundout +25% (small units), NWI patches only	non-easement wetlands and crops equal to ~25% of easement wetland area	plus 1.5%	0.5%	1.38×10^9

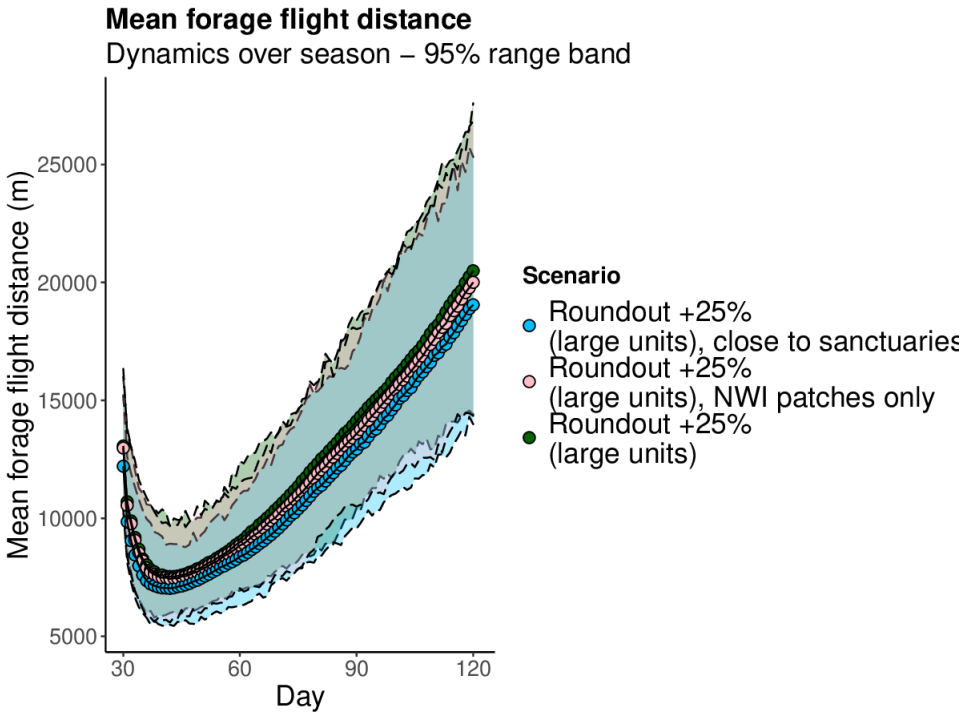


Figure V.13. Mean forage flight distance of mallards (median of 136 replicates, with bilateral 95% values range) for the three placement variants of the large units roundout scenario in the Mississippi Alluvial Valley (MAV) mallard model – random, close to sanctuaries, and National Wetlands Inventory (NWI) patches only.

In contrast, within the group of roundout scenarios, there was a clear effect of selective over random placement. The "close to sanctuaries" roundouts performed better than the "NWI patches only" roundouts, which in turn yielded better gains than the random placement variants. This pattern is not obvious from the food energy gains (Table V.5) and probably depends on the spatial configuration of the seed easements to which the roundout patches were added. It should be kept in mind that the benefits of the two selected location variants *that were realized in the model* are minor (greater proximity to herbaceous wetlands

and roosting locations), while the main expected real-life benefits (less disturbance and hunting pressure, or better quality of restored wetlands) were not modeled (see Methods III C). With this caveat, it appears that the deciding factor in this ranking was a corresponding modest difference in foraging flight distance – daily mean flight distances were largest in the random variant and smallest when patches were added close to easements (Fig. V.13). The one roundout scenario that combined this advantage of short flight distances with the greatest area contiguousness (large unit roundout, close to sanctuaries) was consequently the highest-placed among roundout scenarios.

The aforementioned differences in foraging flight distance between roundout variants were not present in the new easement scenarios (Figure V.12). It is not immediately apparent why adding easement area close to major refuge concentrations resulted in shortened flight distances (and ultimately population gains) for roundout scenarios, but not for new easement scenarios. In fact, the tightening of added easement patch distributions around sanctuaries is more obvious in the latter than in the former, and would be expected to result in similar or stronger changes to flight distances. Instead, flight distances closely matched across all new easement scenarios (not shown). We suggest that this might be the result of an effect discussed in the previous section (Results II B): the dispersed addition of improved patches across the landscape may have "opened up" previously underused areas to exploitation, with mallards drawn to these areas settling into local refuges and foraging in nearby patches under reduced competition. In contrast, improved patches that were added close to well-used refuges are more likely to be surrounded by quickly exploited patches, so that these close-by feeding opportunities would be absent, leading to a more pronounced effect of the distance to the new patches themselves.

In summary, placement of large new easements performed more strongly than roundout approaches even when more targeted placement methods were used. Selection of new easement locations by criteria of closeness to sanctuaries or using NWI-registered wetlands only was largely irrelevant for these scenarios. In contrast, roundouts were improved by selecting NWI-registered locations only, and even more so for locations close to sanctuaries. If existing easements are rounded out to larger extents, it is preferable to choose locations close to sanctuaries, or restore agricultural patches known to have previously been wetlands. In contrast, if entirely new easements are established, these choice restrictions are of lesser importance. However, these conclusions may need to be modified once the as yet unmodeled implications of disturbance-free refuges and agricultural lands with previous wetland hydrology can be assessed. If these are substantial, they may increase the value of selected location placement for completely new easements as well.

D) Enhancing the management of wetlands in existing easements

These scenarios represented various methods of managing wetlands in existing easements to increase their foraging value for waterfowl. The first group of scenarios represented management approaches used to enhance the biomass and/or food quality in foraging patches. These may **increase wetland management of 25% of unmanaged wetland area** in easements to managed, raising food biomass and energy yield; this was applied to either **all types** of wetland (herbaceous and woody) or **herbaceous only**. A further scenario simulated **intensive management of 50% of already managed herbaceous wetlands**, fixing the range of possible food biomass values in affected patches at the 3rd quartile of possible values (from a mean of 75.1 g/m^2 to a fixed 103 g/m^2); this scenario was only tested under standard conditions. The second group of scenarios represented manipulation of the

flooding regime. **Consistent flooding** ensured that all easement patches that flood more often than not now had guaranteed flooding, increasing all existing flooding probabilities of 0.5 or 0.75 to 1. **Consistent minimum flooding** converted the effect of a strong drought in all easement patches into those of a weak drought (i.e., rather than applying a -0.25 drop in flooding probability to all patches, it was only applied to patches with flooding probability 0.75 or 1.0). **Active flooding** simulated the release of stored water at a specified time in the season, setting 25% of easement area to flooded status from that point onwards. This was done either on **day 1 (**the beginning of the simulation), **day 60**, or **day 90**.

Outcomes: (compared to **condition base**)

Under standard conditions, scenarios yielded population gains at end of season of 2.7–12.7%. **Active flooding (day 90)** had the largest population gain [+12.7%; +21,750 mallards].

Under flood conditions, scenarios yielded gains of 0.1–0.7%. **Increased wetland management (all types)** had the largest gain [+0.7%; +1,450 mallards].

Under weak drought conditions, scenarios yielded population changes of -7.5% to +13.5%. **Increased wetland management (all types)** had the largest gain [+13.5%; +21,500 mallards].

Under strong drought conditions, scenarios yielded population changes of -16% to +2436%. **Active flooding (day 60)** had the largest gain [+2436%; +30,450 mallards].

Table V.6. Metrics of total population at end of season (day 120) in the Mississippi Alluvial Valley (MAV) mallard model, for scenario group D under standard and flood conditions. %Cco: % change from condition base (base scenario under relevant environmental conditions: Standard, Flood, Weak drought, or Strong drought); %Cst: change from base scenario, standard conditions; Pop: median population; CV: coefficient of variation. Entries are ordered by decreasing %Cco

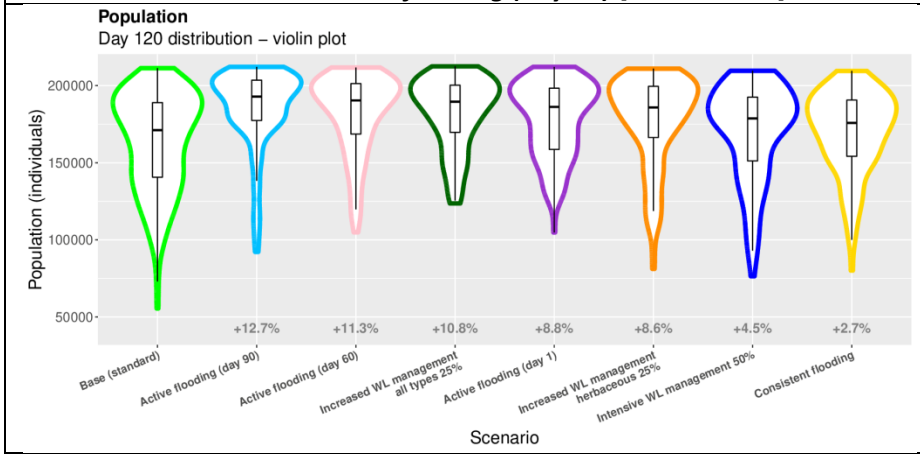
Conditions	***Scenario***	***%Cco***	***%Cst***	***Pop***	***CV***
Flood	Increased wetland management all types 25%	0.7	21.8	208350	0.04
Flood	Increased wetland management herbaceous 25%	0.1	21.1	207200	0.04
Standard	Active flooding (day 90)	12.7	12.7	192850	0.14
Standard	Active flooding (day 60)	11.3	11.3	190400	0.14
Standard	Increased wetland management all types 25%	10.8	10.8	189550	0.13
Standard	Active flooding (day 1)	8.8	8.8	186200	0.14
Standard	Increased wetland management herbaceous 25%	8.6	8.6	185850	0.16
Standard	Intensive wetland management herbaceous 50%	4.5	4.5	178750	0.18
Standard	Consistent flooding	2.7	2.7	175800	0.16

Table V. 6. Continued.

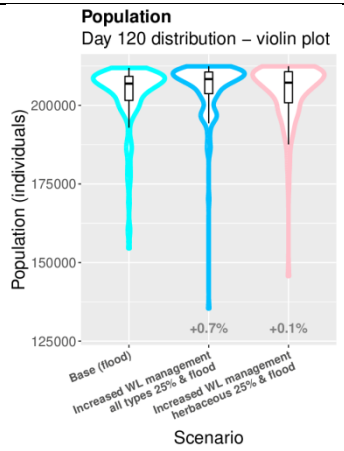
Conditions	***Scenario***	***%Cco***	***%Cst***	***Pop***	***CV***
Weak drought	Increased wetland management all types 25%	13.5	5.8	180950	0.19
Weak drought	Active flooding (day 90)	10.9	3.3	176800	0.21
Weak drought	Increased wetland management herbaceous 25%	10.1	2.6	175500	0.21
Weak drought	Active flooding (day 60)	7.9	0.6	172050	0.22
Weak drought	Consistent flooding	-3.2	-9.8	154350	0.26
Weak Drought	Active flooding (day 1)	-7.5	-13.8	147450	0.26
Strong drought	Active flooding (day 60)	2436	-81.5	31700	0.51
Strong drought	Active flooding (day 1)	2108	-83.9	27600	0.16
Strong drought	Active flooding (day 90)	2104	-83.9	27550	0.61
Strong drought	Consistent minimum flooding	800	-93.4	11250	0.73
Strong drought	Consistent flooding	124	-98.4	2800	0.96
Strong drought	Increased wetland management all types 25%	36	-99	1700	1.1

Figure V.14 Simulation results when enhancing the management of wetlands (WL) in existing easements in the Mississippi Alluvial Valley (MAV) mallard model – overview. Note that y-axis scale varies between plots.

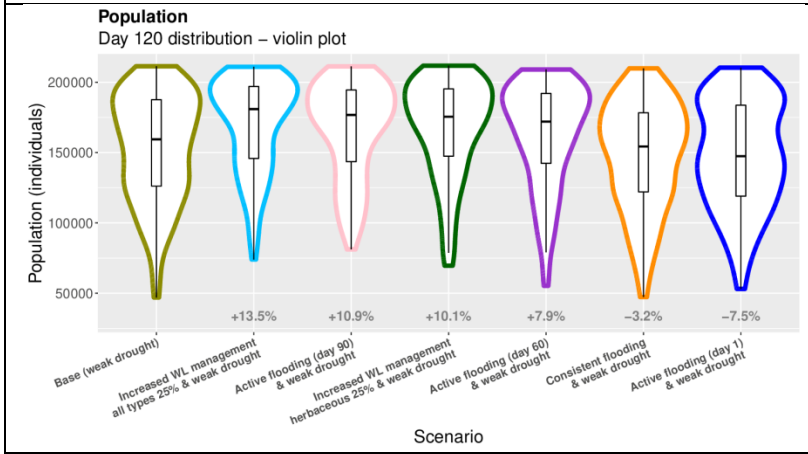
Standard conditions largest population at end of season:
Active flooding (day 90) [Base +12.7%]



Flood conditions largest population at end of season:
Increased wetland management (all types) [Flood +0.7%]



Weak drought conditions largest population at end of season:
Increased wetland management [all types] [Weak drought +13.5%]



Strong drought conditions largest population at end of season:
Active flooding in strong drought (day 60) [Strong drought +2436%]

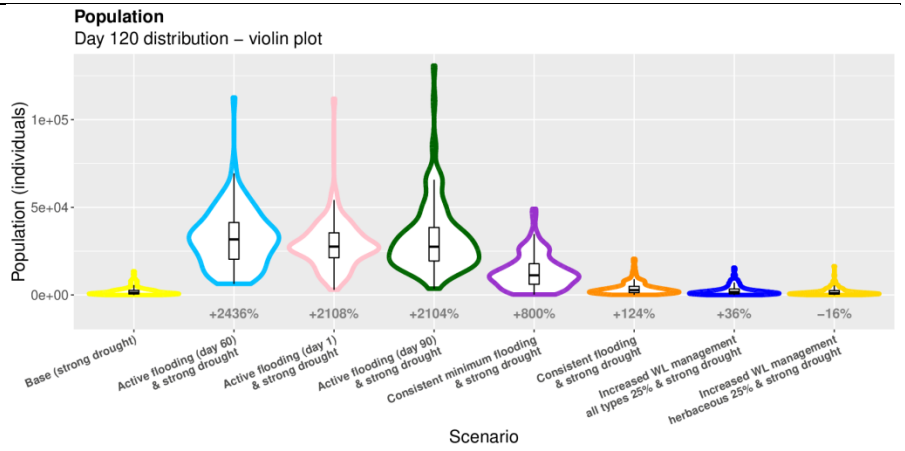
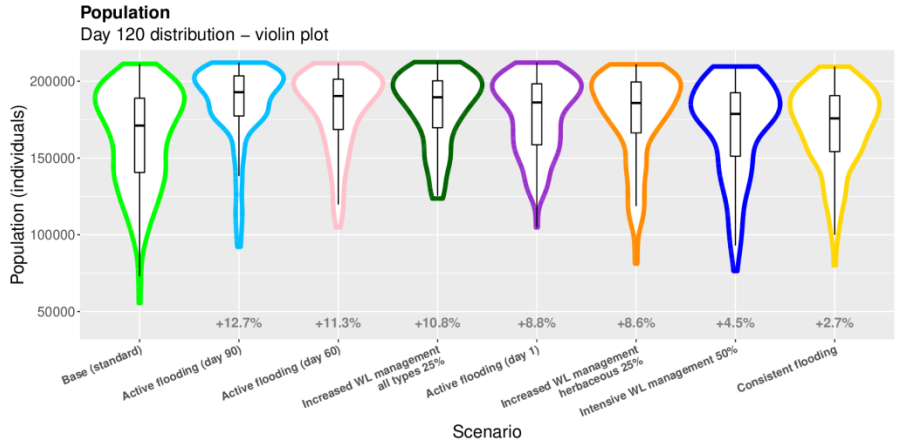


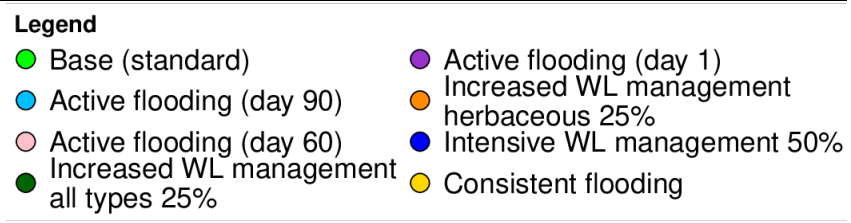
Figure V.15 Simulation results when enhancing the management of wetlands (WL) in existing easements in the Mississippi Alluvial Valley (MAV) mallard model –

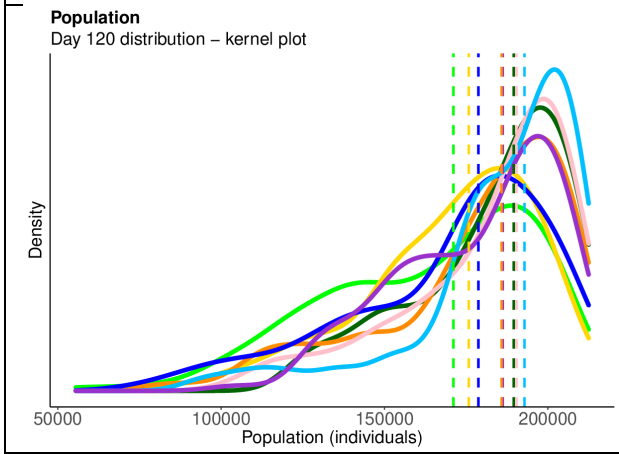
Standard environmental conditions. The shaded areas represent bilateral 95% value ranges.

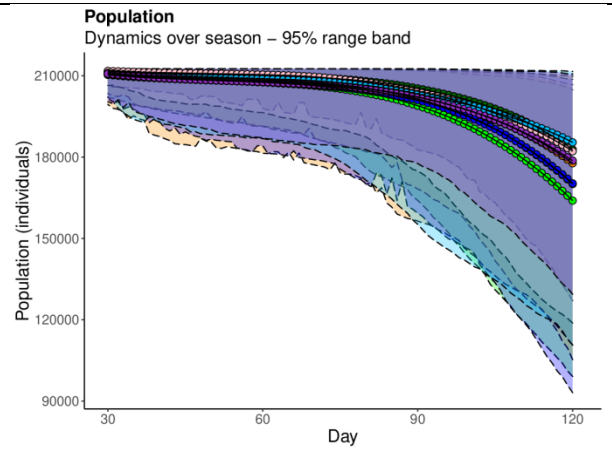
Scenarios: ● ***Increased wetland management +25% (all types)*** ● ***Increased wetland management +25% (herb.)*** ● ***Intensive wetland management +50% (herb.)*** ● ***Consistent flood*** ● ***Active flooding (day 60)*** ● ***Active flooding (day 90)*** ● *Base (standard)*

Largest population at end of season, under standard conditions: ***Active flooding (day 90)*** [Base +12.7%]









To illustrate dynamics over the season, this set is split up into two parts on the following two pages:

A) the top three scenarios
B) the remaining four scenarios

Figure V.16 Simulation results when enhancing the management of wetlands (WL) in existing easements in the Mississippi Alluvial Valley (MAV) mallard model - **Standard** environmental conditions. The shaded areas represent bilateral 95% value ranges.

Subset A – top three scenarios

Scenarios: ● ***Active flooding (day 90)*** ● ***Active flooding (day 60)*** ● ***Increased wetland management +25% (all types)*** ● *Base (standard)*

Largest population at end of season, under standard conditions: ***Active flooding (day 90)*** [Base +12.7%]

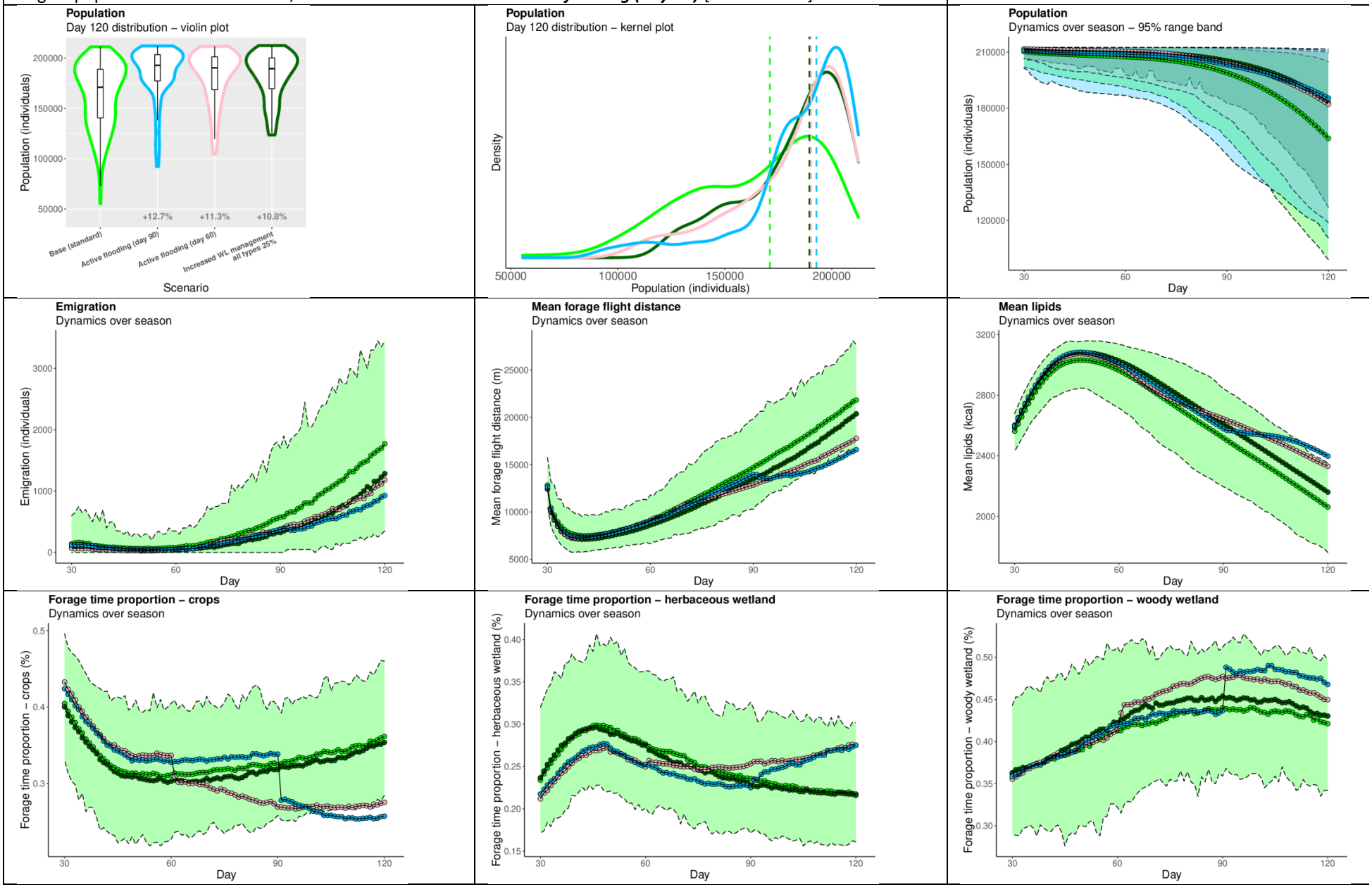


Figure V.17 Simulation results when enhancing the management of wetlands (WL) in existing easements in the Mississippi Alluvial Valley (MAV) mallard model - Standard environmental conditions. The shaded areas represent bilateral 95% value ranges.

Subset B – remaining four scenarios

Scenarios: ● Active flooding (day 1) ● Increased wetland management +25% (herb.)

● Intensive wetland management 50% ● Consistent flood ● *Base (standard)*

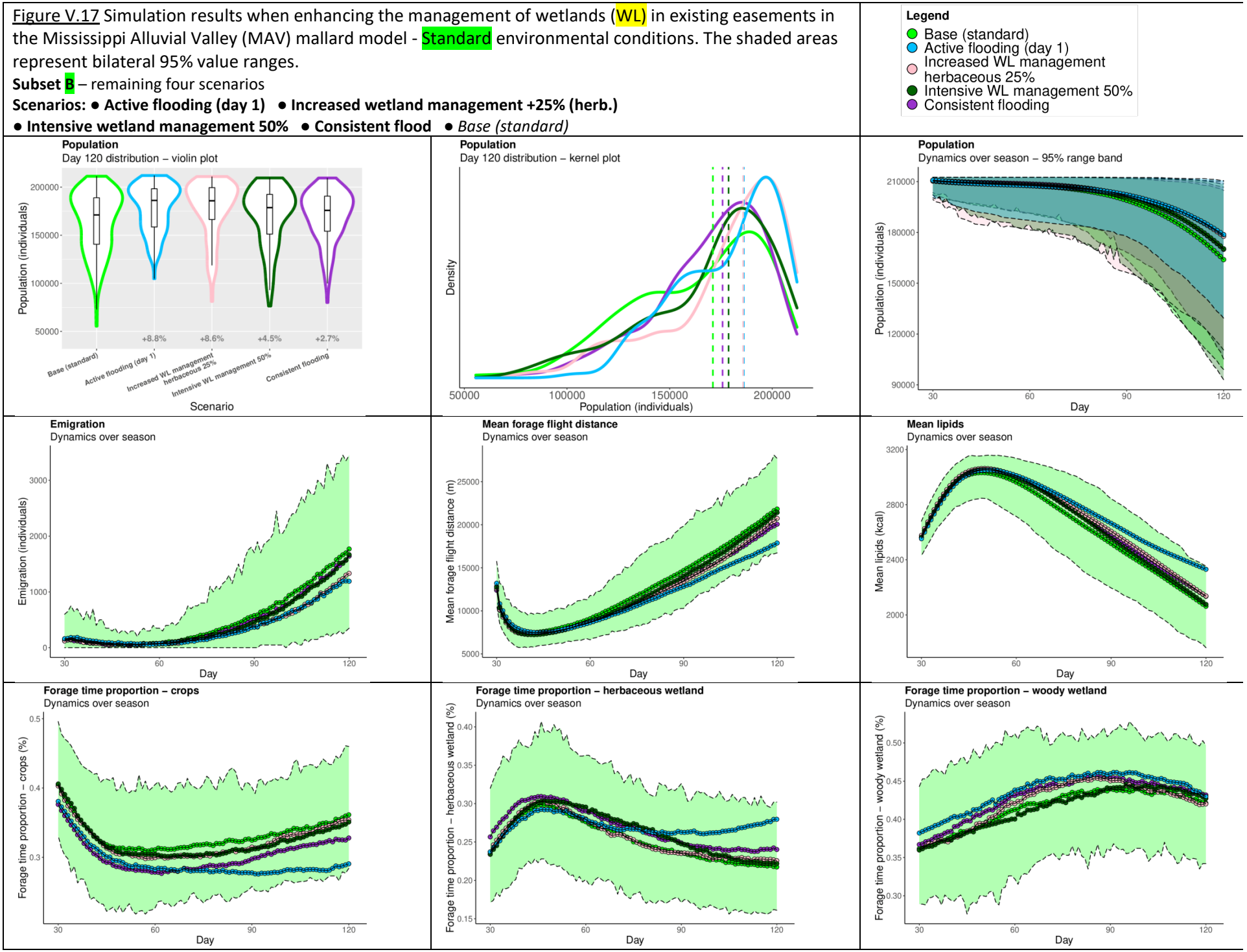


Figure V.18 Simulation results when enhancing the management of wetlands (WL) in existing easements in the Mississippi Alluvial Valley (MAV) mallard model - Flood conditions. The shaded areas represent bilateral 95% value ranges.

Scenarios: { ● Increased wetland management +25% (all types)

● Increased wetland management +25% (herb.) } & flood ● *Base (flood)*

Largest population, under flood conditions: Increased wetland management +25% (all types) [Flood +0.7%]

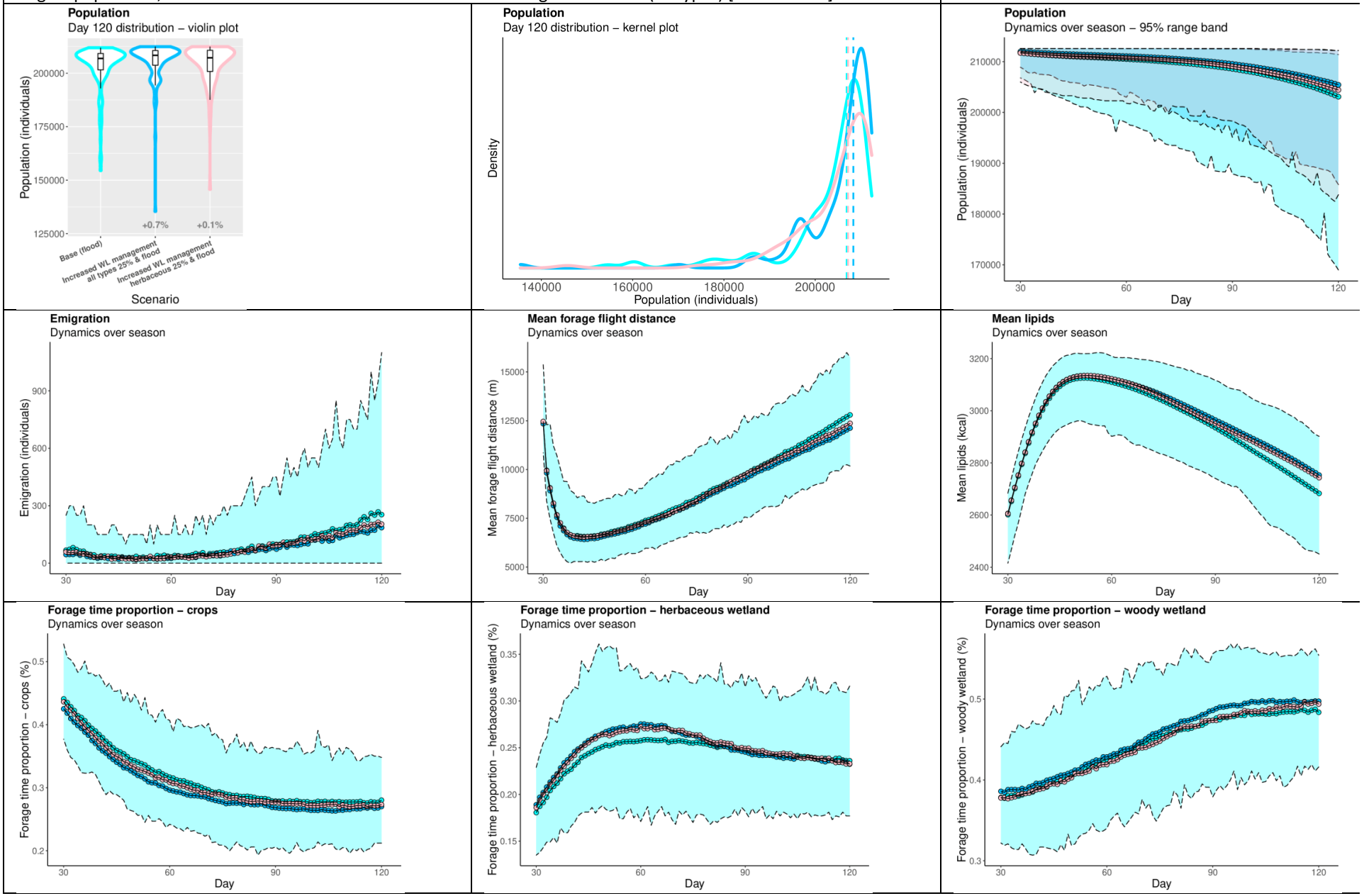
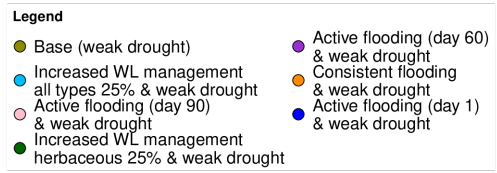
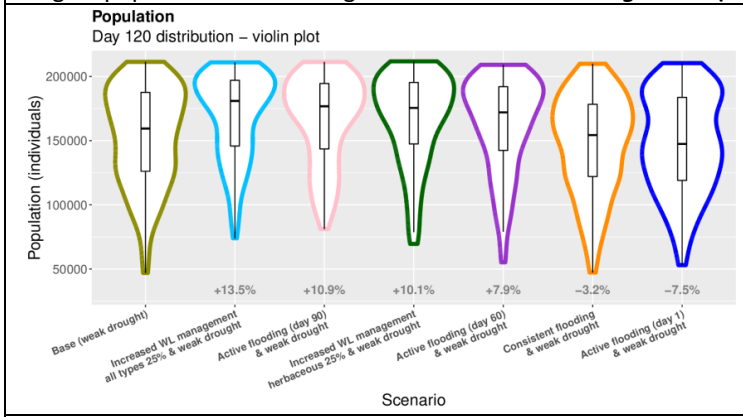


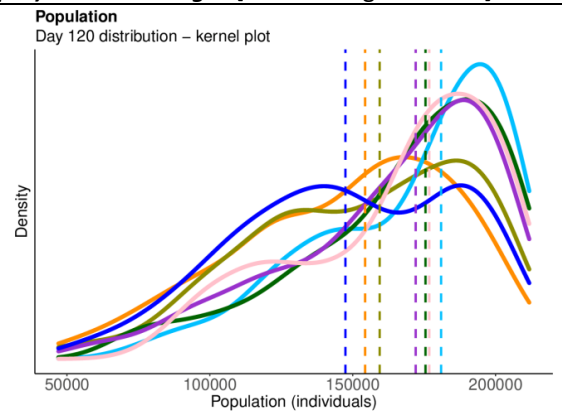
Figure V.19 Simulation results when enhancing the management of wetlands (WL) in existing easements in the Mississippi Alluvial Valley (MAV) mallard model – **Weak drought** conditions. The shaded areas represent bilateral 95% value ranges.

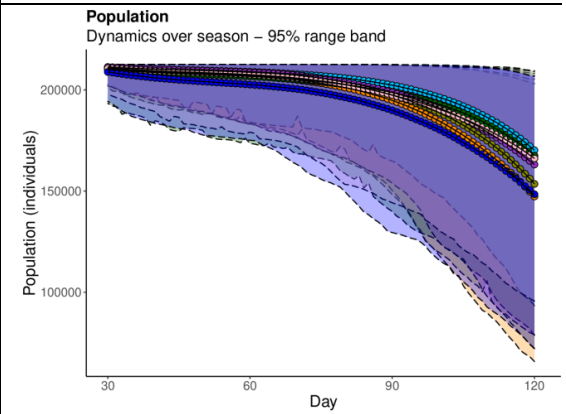
Scenarios: ***{ ● Increased wetland management +25% (all types) ● Increased wetland management +25% (herb.) ● Intensive wetland management +50% (herb.) ● Consistent flood ● Active flooding (day 1)***
● Active flooding (day 60) ● Active flooding (day 90) } & weak drought ● *Base (weak drought)*

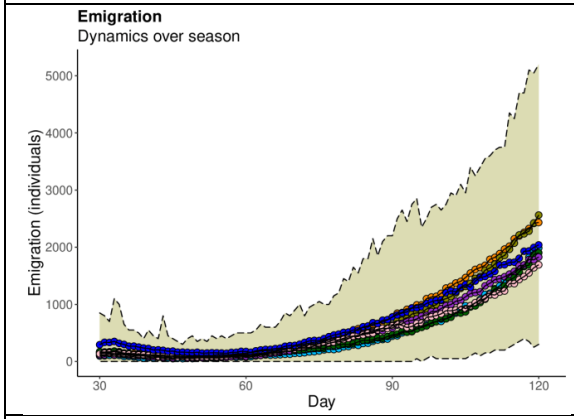
Largest pop. under weak drought: ***Increased wetland mgt +25% (all types) & weak drought*** [Weak drought +13.5%]

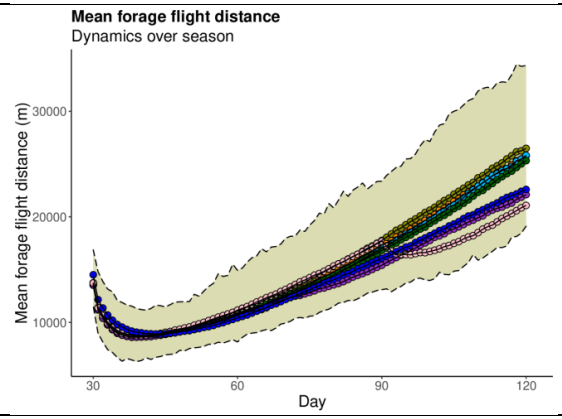


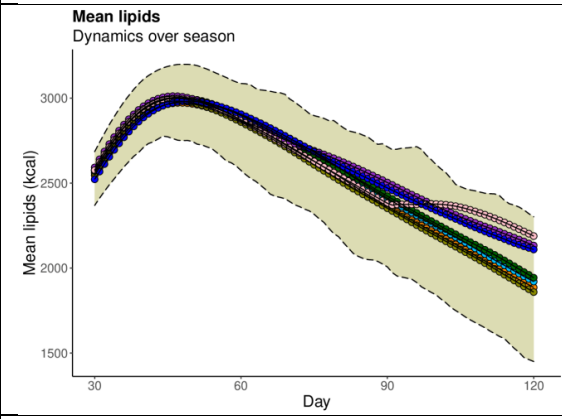


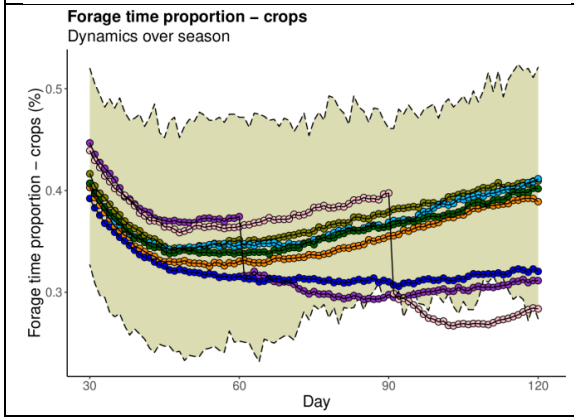


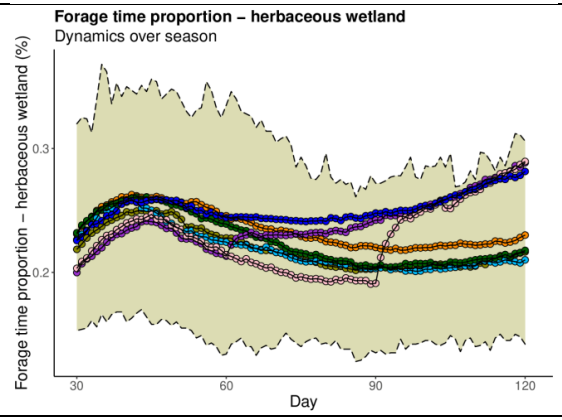












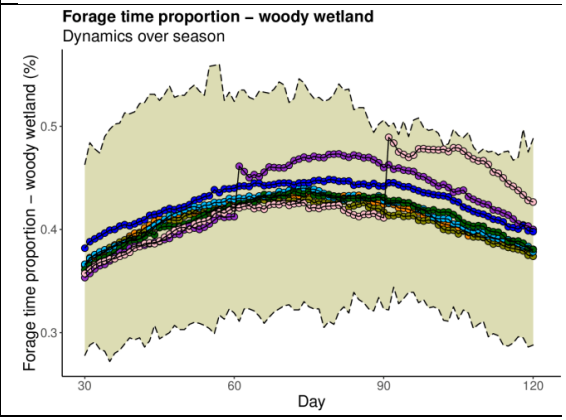
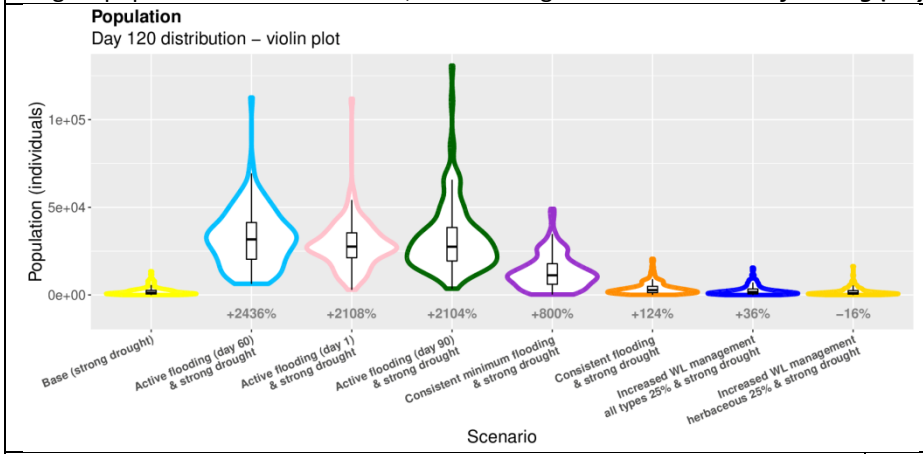
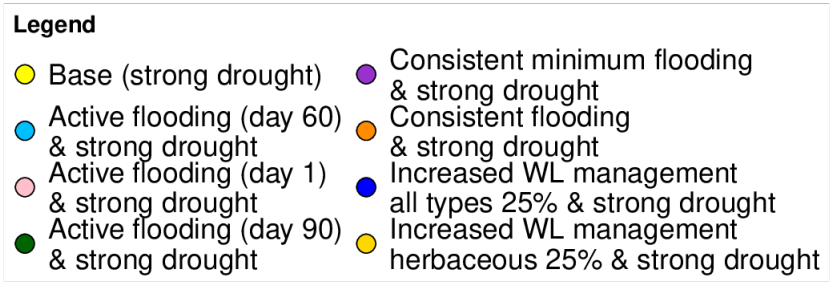


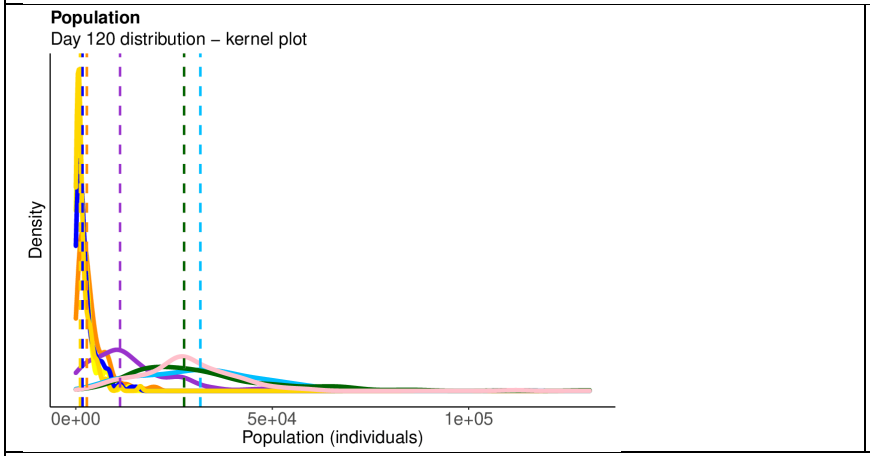
Figure V.20 Simulation results when enhancing the management of wetlands (WL) in existing easements in the Mississippi Alluvial Valley (MAV) mallard model – **Strong drought** conditions. The shaded areas represent bilateral 95% value ranges.

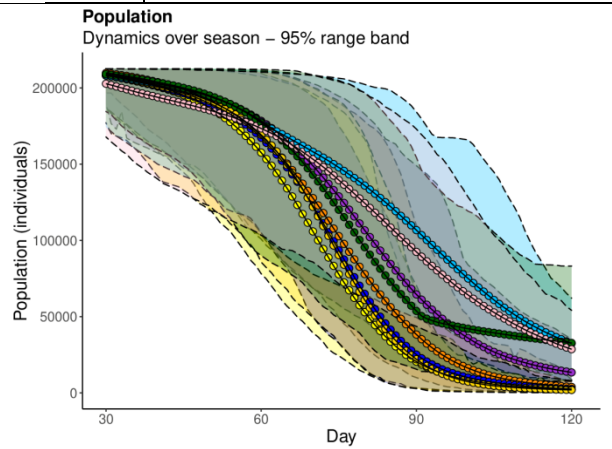
Scenarios: ***{ ● Active flooding (day 1) ● Active flooding (day 60) ● Active flooding (day 90) ● Consistent minimum flood ● Increased wetland management +25% (all types) ● Increased wetland management +25% (herb.) ● Consistent flood } & strong drought*** ● *Base (strong drought)*

Largest population at end of season, under drought conditions: ***Active flooding (day 60) & strong drought*** [Strong drought +2436%]









To illustrate dynamics over the season, this set is split up into two parts on the following two pages:

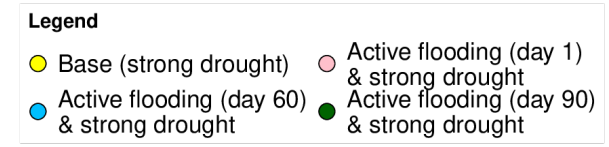
A) the top three scenarios
B) the remaining four scenarios

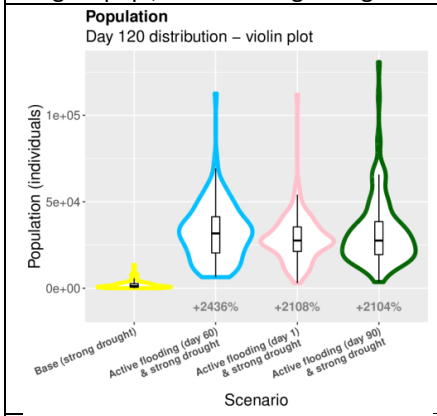
Fig. V.21 Simulation results when enhancing the management of wetlands (WL) in existing easements in the Mississippi Alluvial Valley (MAV) mallard model – **Strong drought** conditions. The shaded areas represent bilateral 95% value ranges.

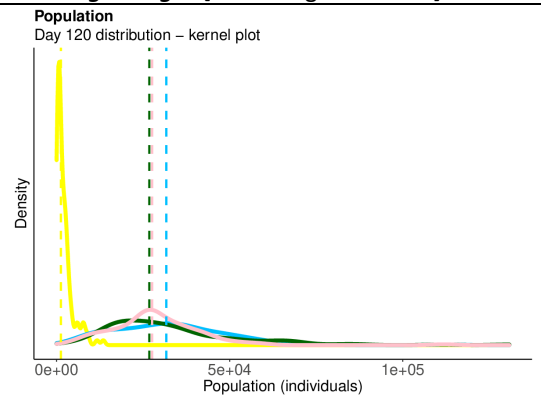
SUBSET A – top three scenarios

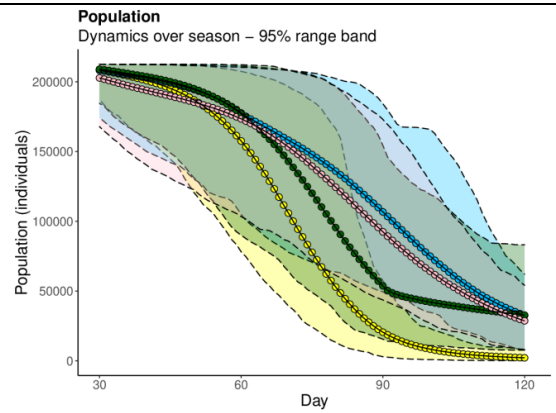
Scenarios: ***{ ● Active flooding (day 1) ● Active flooding (day 60) ● Active flooding (day 90) } & strong drought*** ● *Base (strong drought)*

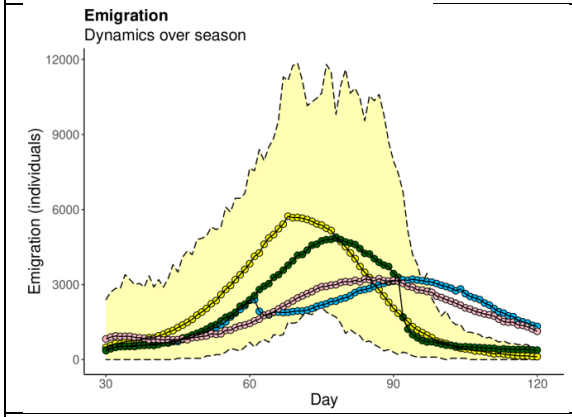
Largest pop., under strong drought: ***Active flooding (day 60) & strong drought*** [Str. drought +2436%]

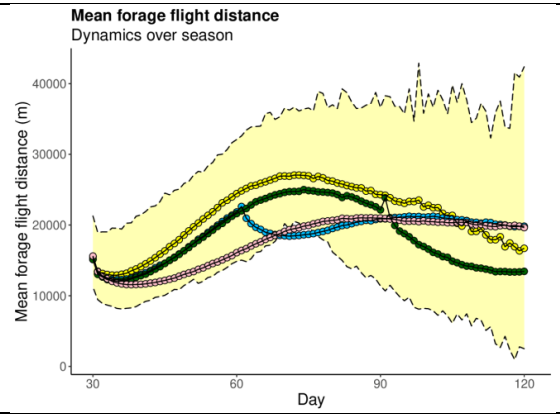


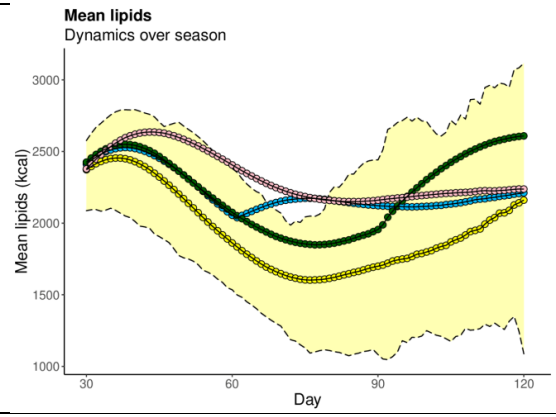


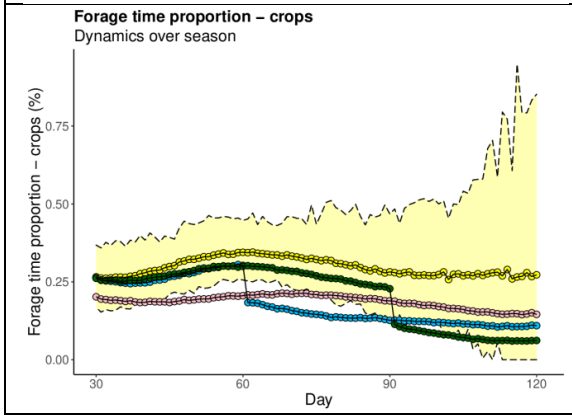


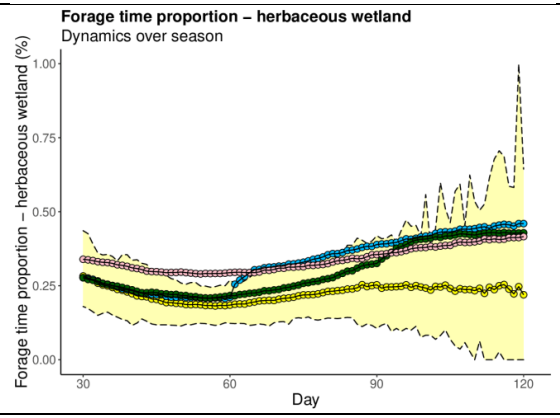












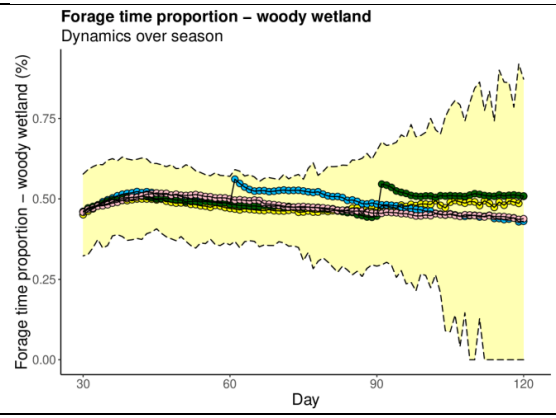


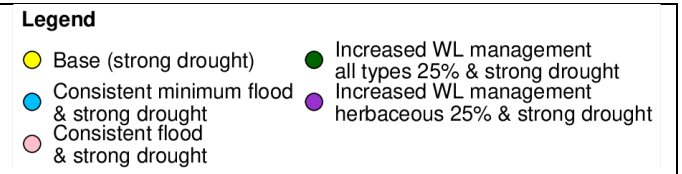
Fig. V.22 Simulation results when enhancing the management of wetlands (WL) in existing easements in the Mississippi Alluvial Valley (MAV) mallard model – **Strong drought** conditions. The shaded areas represent bilateral 95% value ranges.

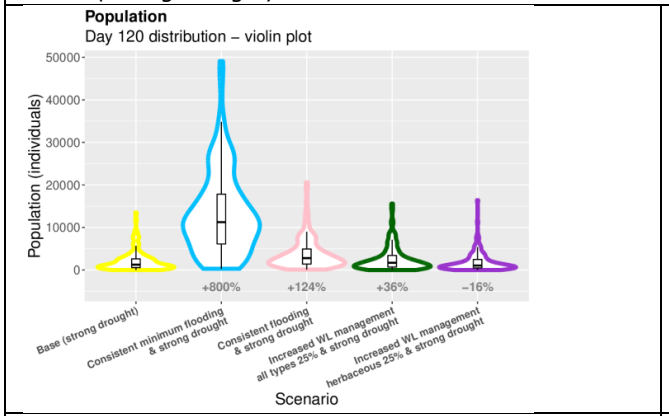
SUBSET B – remaining four scenarios

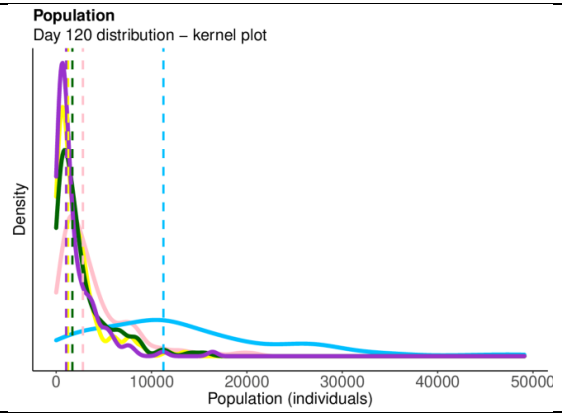
Scenarios: ***{ ● Consistent minimum flood ● Increased wetland management +25% (all types)***

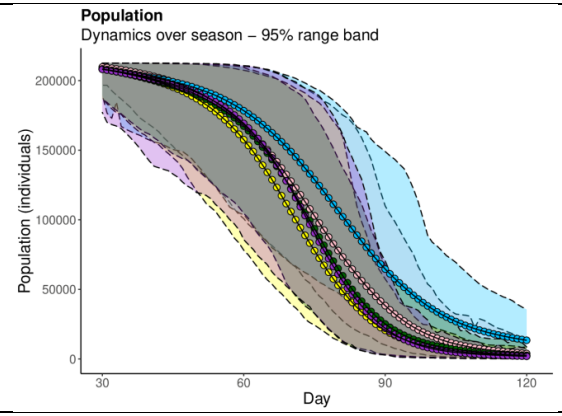
● Increased wetland management +25% (herb.) ● Consistent flood } & strong drought

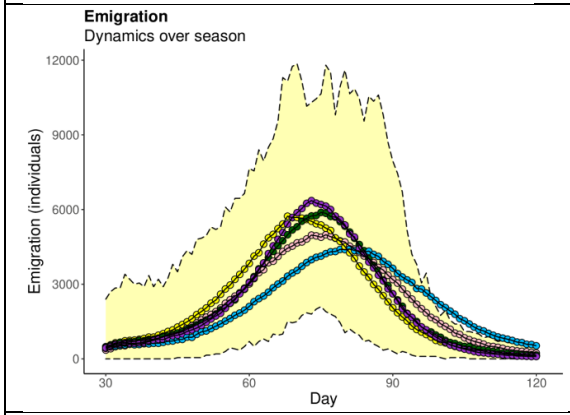
● Base (strong drought)

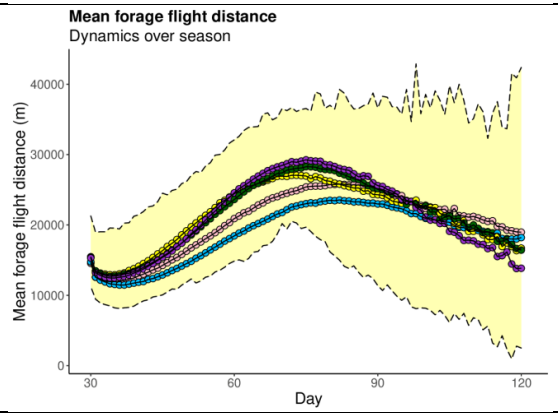


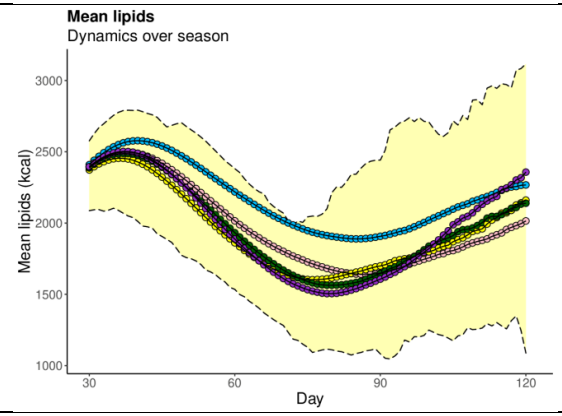


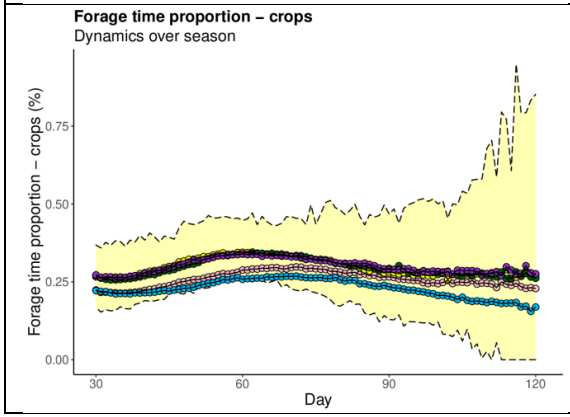


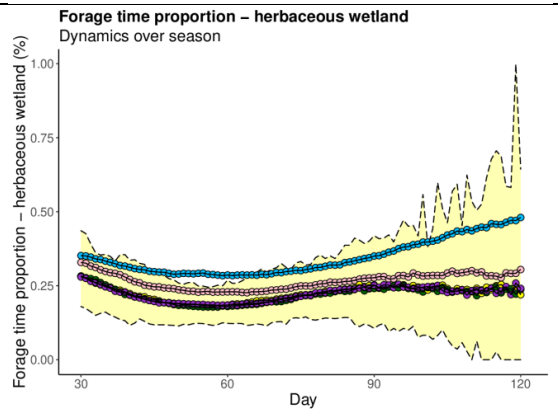


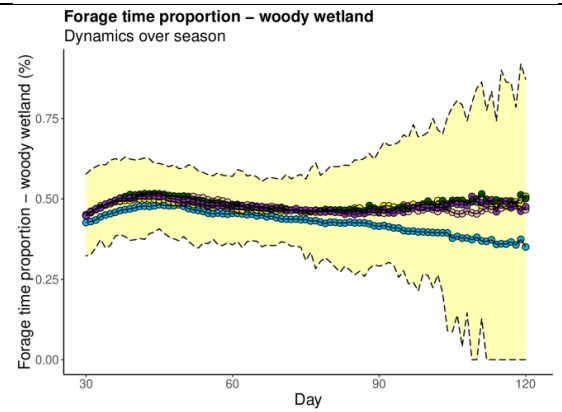












The most effective management approaches under standard conditions consisted of active flooding later in the year, with day 90 flooding yielding +12.7% population abundance (+21,750 mallards) and day 60 flooding +11.3% (+19,300 mallards). Active flooding at the beginning of the season (day 1) was still very effective (+8.8%; +15,100 mallards), but was surpassed by increased wetland management [all types] (+10.8%; +18,450 mallards). Late active flooding also performed well under weak drought conditions (+10.9% / +17,350 mallards for day 90 flooding), but ranked results were interspersed with increased wetland management (*in the following,* ***IWM***) approaches, and IWM [all types] performed best (+13.5%; +21,500 mallards). Under strong drought, active flooding at any time was substantially more effective than any other approach, yielding a gain of up to 30,450 mallards for day 60 flooding. Under flood conditions, where only the IWM subgroup could be sensibly tested, increasing the management of both herbaceous and woody wetlands had little effect (+1,450 mallards) and had close to no effect if restricted to herbaceous wetlands only (+300 mallards).

The scenarios in this group were diverse, affecting different proportions of the total foraging area and adding different amounts of food energy to the map (Table V.7). Active flooding added the largest amount of energy, followed by consistent minimum flooding (which was only applicable under strong drought conditions).

Table V.7. Manipulated foraging area, percentage of total foraging area affected, and energy added to map, for each scenario in scenario group D of the Mississippi Alluvial Valley (MAV) mallard model.

Scenario	***Manipulated area***	***Percentage of total foraging area affected***	***Energy added to map relative to Base (standard) (kcal)***
Increased wetland management 25% (all types)	25% of easement wetland area	1.5%	0.44×10^9
Increased wetland management 25% (herbaceous)	25% of easement herbaceous wetland area	0.3%	0.17×10^9
Intensive wetland management 50% (herbaceous)	50% of easement herbaceous wetland area that is already 'managed'	0.4%	0.52×10^9
Consistent flooding	Easement wetlands with flooding probability ≥ 0.5	1.6%	1.94×10^9
Consistent minimum flooding	Easement wetlands with flooding probability < 0.5	5.6%	3.56×10^9 (vs strong drought – not applicable under other conditions)
Active flooding	25% of easement wetland area (including patches with 0% flooding probability under standard conditions)	1.5%	3.68×10^9

Active flooding led to rapid shifts in habitat use under all conditions at the point of water release. The shift away from crops and into herbaceous and woody wetlands was the expected effect when only wetland patches (in easements) received the extra flooding, while crops continued under prevailing conditions. These increases in habitat use were dramatic for late onset of flooding (day 60 or day 90); in the case of onset on day 1 (from start of simulation), the trajectory of increased habitat use with flooding existed from the start. This strong effect was partly caused by active flooding having the capability to flood patches that had 0% flooding probability under standard conditions. These patches made up ~25% of the total foraging area and played no part

in mallard foraging unless under flooding conditions, when they were upgraded to 25% flooding probability. Active flooding was the only tested management approach that activated these patches, which contributed to its strong effect relative to other management types.

Under all conditions, the magnitude of habitat shifts followed a day 90 – day 60 – day 1 flooding schedule ranking. For standard or weak drought conditions, this ranking also held for end-of-season population abundance, indicating that active flooding was more effective when implemented later in the season. Under strong drought, day 60 flooding worked best, whereas day 90 and day 1 flooding dates both yielded lower results. However, inspection of the population trajectories at end of season (Figure V.21 - population dynamics) revealed that just a few days beyond the simulation's cutoff on day 120, the beneficial effects of the day 90 treatment would be expected to surpass those of the other variants, establishing the same ranking (this is also suggested by the flight distance and lipid storage conditions – Figure V.21, middle row).

This outcome was probably due to the convergence of flooding at these later points with the shift in forage use from crops to wetlands that occurred in mid-to-late season in all scenarios (Figures IV.5, IV.6). Flooding later in the season boosted the use of those habitat types that were gaining in importance for mallards at the same time. In contrast, day 1 flooding happened at a point where it benefited a smaller proportion of the population, because many mallards were still exploiting crops. It appears that ensuring partial flood conditions from the start of the season (day 1) was always the least efficient active flooding choice. Under weak drought, this actually resulted in lower-than-base median population outcomes (Figure V.19).

The two IWM scenarios (upgrading 25% of unmanaged easement wetlands to managed status, thereby adding more biomass per patch) mattered only under standard or weak drought conditions, while under flooding or strong drought neither IWM option made a substantial difference to the end-of-season outcome. Under standard conditions, IWM [all types] yielded gains only slightly below the two late active flooding scenarios, while under weak drought, this scenario ranked first by a more substantial margin. The IWM scenarios achieved these gains without engendering a shift in habitat use comparable to the active flooding scenarios (Figures V.16, V.19 – bottom row) because they did not flood additional patches. Rather, they increased the reservoir of food biomass present in already flooded patches, delaying their depletion. This strategy appears to be more effective under weak drought than under standard conditions.

The IWM scenario that affected both herbaceous and woody patches ('all types', Table V.7) predictably performed better than the one that upgraded herbaceous patches only (a difference of 3,700 mallards under standard conditions and 5,450 mallards under weak drought conditions). However, the latter (upgrading herbaceous patches) required manipulation of only 1/5 of the area of the former (Table V.7); this might merit consideration as a worthwhile trade-off.

The scenario for intensive management of 50% of already managed wetlands (guaranteeing a fixed biomass ~1/3 greater than the mean biomass of this patch type) was only tested under standard conditions. It affected about half the area proportion of the IWM (herbaceous) scenario, but added three times the food energy to the map (Table V.7). However, it performed relatively poorly and yielded only about half the population gain of the other scenario (+7,650) with population dynamics under this scenario generally following those of the base scenario. This approach may constitute an excessive case of the "increase biomass reservoir depth" strategy that was also employed in the IWM scenarios. Here only the single patch category that already had the

most abundant reservoirs of food biomass was enhanced further – to little effect, because these patches rarely came close to depletion even before the manipulation.

It is not surprising that under strong drought (Figures V.20–V.22), all flood manipulation scenarios performed better than the increased management scenarios, which provided little to no benefit. The active flood variants were most effective by a large margin, creating small islands of inundated habitat in a drought-impacted landscape. Consistent minimum flooding (a scenario only applicable under strong drought, where it prevents any easement patch from falling dry completely) also showed substantial gains (+10,000 mallards). However, this scenario was applied to a much larger proportion of the total foraging area than the other scenarios (5.6% of area; Table D2), making it debatable whether a similar approach would yield a favorable return on management effort if implemented. In contrast, consistent flooding (ensuring that patches with flooding probability 0.5 or 0.75 always flood) had much smaller gains (+1,550 mallards). This approach performed poorly under all tested conditions, showing dynamics that mostly resembled the condition base. Under standard conditions, the probable cause was that this manipulation tended to boost the availability of wetlands that were already embedded in areas of general high flooding, and did little to open up new map areas. Under strong drought, there existed very few candidate patches with mid- to high flooding that the manipulation could be applied to.

The worse-than-base performance of both consistent flooding and day 1 active flooding under weak drought (Figure V.19) was probably driven by a shared mechanism. Both scenarios showed the expected increased flooding vs condition base in all wetland categories; e.g., managed herbaceous and woody wetlands in day 1 active flooding gained an average of 12–13% flooding probability, and the map gained 3.5×10^9 kcal in food energy. Thus, additional resources were clearly available, but could not be efficiently exploited by mallards. A likely explanation is that because all scenarios in this group enhanced the quality of easement wetlands only, they created compact attractive areas on the map, as the large majority of the foraging area was not altered. This resulted in mallard populations becoming concentrated in easements and led to preferential exploitation of these areas and, if the affected patches became depleted, a reliance of large numbers of birds on nearby patches and/or a need to disperse over longer distances. Under standard or abundance conditions, there do not seem to be perceptible consequences for the use of this mechanism. Under strong drought, a smaller population is already expected to be concentrated in high-yield spots and would have benefited from their enhancement. However, under weak drought conditions, further landscape interactions may become important.

Both of the weak drought scenarios in question, consistent flooding and day 1 active flooding, had a noticeably broad range of outcome distributions across replicates (Figure V.19 – violin/kernel plots). This is true in general for scenarios that were moderately close to the base weak drought condition (Figure V.9 - violin/kernel plots); moderate scarcity conditions appear to promote a wider spread of common outcomes in the simulation than standard, abundance or strong scarcity conditions. This was particularly pronounced for day 1 active flooding, which displayed a bimodal distribution in population abundance at end of season (Figure V.19 – kernel plot) as well as for most other metrics throughout the season (not shown). One group of outcomes was centered around population abundances similar to those of the late-season active flooding scenarios, whereas, the second group was centered around population abundances that were ~20-30% lower. This suggests that the spatial relationship between highly flooded, preferentially exploited easement "islands" and the low-flooding surrounding landscape was heavily influenced by

the randomly flooded composition of that landscape, and that strongly favorable as well as worse-than-baseline configurations can occur. Under this interpretation, it appears that under weak drought conditions these two scenarios created sufficiently strong attractors to influence the concentration of birds on the map, but did not offer sufficient foraging gains to offset the negative consequences of such localized depletion in a low-yield landscape.

In summary, active flooding of a portion of easement wetlands late in the season was the most effective wetland management approach under standard and strong drought conditions, and among the most effective approaches under weak drought conditions. Active flooding early in the season was still productive under standard and strong drought conditions, but could have highly variable outcomes under weak drought. Increasing the management level of a portion of unmanaged herbaceous and woody wetlands yielded favorable results under standard conditions, with the best results under weak drought; applying this treatment to only herbaceous wetlands may be more efficient but could reduce population gains. Under flood conditions, these increased management scenarios had no substantial effect. Under strong drought conditions, only flooding manipulations were effective, although consistent minimum flooding of low-flooding patches had only marginal returns. Active flooding at any time of year had large benefits under strong drought. More intensive management of a portion of already managed herbaceous wetlands was largely ineffective for mallard populations at a regional scale. Ensuring guaranteed flooding of frequently flooded wetlands performed poorly under all conditions.

E) Increasing population size at end of season (all management methods)

This section includes all previously discussed conservation and management scenarios (for both **easement area increase** and **enhancement of existing easement management**) and evaluates their effectiveness in increasing end-of-season population abundance in context. For details on included scenarios, see Results II B, C, and D.

Outcomes: (compared to **condition base**)

Under standard conditions, scenarios yielded population gains at end of season of 2.7–12.7%. **Active flooding (day 90)** had the largest population gain [+12.7%; +21,750 mallards].

Under flood conditions, scenarios yielded gains of 0.1–0.9%. **New easements +25% (small units)** had the largest gain [+0.9%; +1,850 mallards].

Under weak drought conditions, scenarios yielded population changes of -7.5% to +16.2%. **New easements (large units)** had the largest gain [+16.2%; +25,800 mallards].

Under strong drought conditions, scenarios yielded population changes of -16% to +2436%. **Active flooding (day 60)** had the largest gain [+2436%; +30,450 mallards].

Table V.8. Metrics of total population abundance at end-of-season (day 120) in the Mississippi Alluvial Valley (MAV) mallard model, for scenario group E, under standard conditions. %Cco: % change from condition base (base scenario under relevant environmental conditions: Standard, Flood, Weak drought, or Strong drought); %Cst: change from base scenario, standard conditions; Pop: median population; CV: coefficient of variation. Entries are ordered by decreasing %Cco

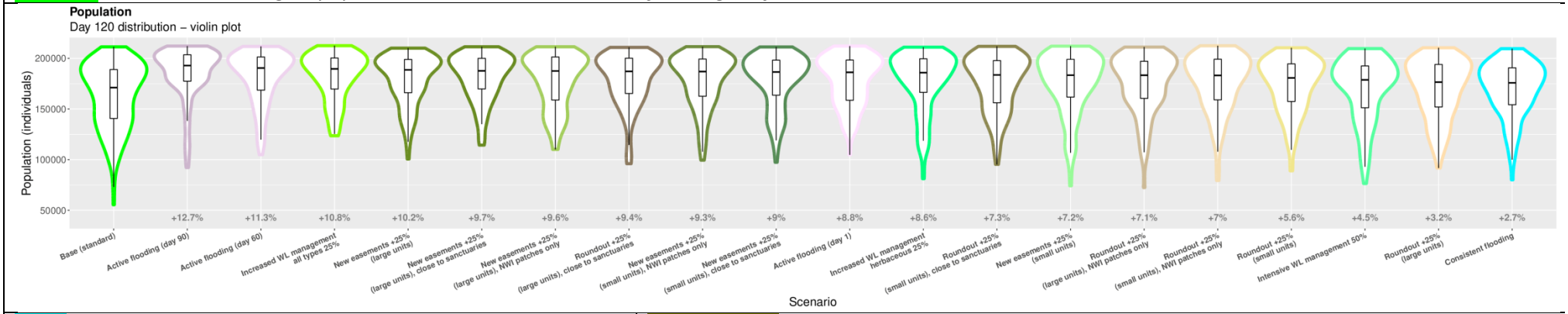
Conditions	*Scenario*	*%Cco*	*%Cst*	*Pop*	*CV*
Standard	Active flooding (day 90)	12.7	12.7	192850	0.14
Standard	Active flooding (day 60)	11.3	11.3	190400	0.14
Standard	Increased wetland management all types 25%	10.8	10.8	189550	0.13
Standard	New easements +25% (large units)	10.2	10.2	188600	0.14
Standard	New easements +25% (large units), close to sanctuaries	9.7	9.7	187650	0.13
Standard	New easements +25% (large units), NWI patches only	9.6	9.6	187500	0.15
Standard	Roundout +25% (large units), close to sanctuaries	9.4	9.4	187150	0.14
Standard	New easements +25% (small units), NWI patches only	9.3	9.3	186950	0.15
Standard	New easements +25% (small units), close to sanctuaries	9	9	186500	0.15
Standard	Active flooding (day 1)	8.8	8.8	186200	0.14
Standard	Increased wetland management herbaceous 25%	8.6	8.6	185850	0.16
Standard	Roundout +25% (small units), close to sanctuaries	7.3	7.3	183600	0.16
Standard	New easements +25% (small units)	7.2	7.2	183350	0.17
Standard	Roundout +25% (large units), NWI patches only	7.1	7.1	183300	0.16
Standard	Roundout +25% (small units), NWI patches only	7	7	183150	0.16
Standard	Roundout +25% (small units)	5.6	5.6	180700	0.15
Standard	Intensive wetland management herbaceous 50%	4.5	4.5	178750	0.18
Standard	Roundout +25% (large units)	3.2	3.2	176500	0.17
Standard	Consistent flooding	2.7	2.7	175800	0.16

Table V.8 continued. Metrics of total population at end-of-season (day 120) in the Mississippi Alluvial Valley (MAV) mallard model, for scenario group E, under flood, weak drought, or strong drought conditions. %Cco: % change from condition base (base scenario under relevant environmental conditions: Standard, Flood, Weak drought, or Strong drought); %Cst: change from base scenario, standard conditions; Pop: median population; CV: coefficient of variation. Entries are ordered by decreasing %Cco.

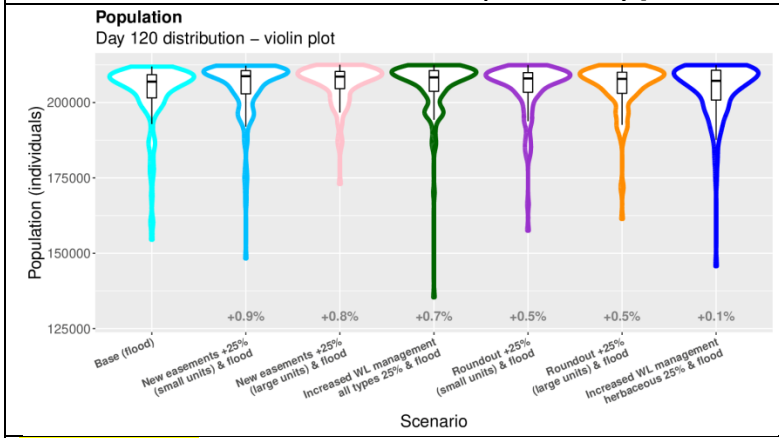
Conditions	***Scenario***	***%Cco***	***%Cst***	***Pop***	***CV***
Flood	New easements +25% (small units)	0.9	22	208750	0.05
Flood	New easements +25% (large units)	0.8	21.9	208600	0.03
Flood	Increased wetland management all types 25%	0.7	21.8	208350	0.04
Flood	Roundout +25% (small units)	0.5	21.6	208000	0.04
Flood	Roundout +25% (large units)	0.5	21.5	207850	0.04
Flood	Increased wetland management herbaceous 25%	0.1	21.1	207200	0.04
Weak drought	New easements +25% (large units)	16.2	8.3	185250	0.20
Weak drought	Increased wetland management all types 25%	13.5	5.8	180950	0.19
Weak drought	Active flooding (day 90)	10.9	3.3	176800	0.21
Weak drought	Increased wetland management herbaceous 25%	10.1	2.6	175500	0.21
Weak drought	New easements +25% (small units)	9	1.6	173800	0.21
Weak drought	Active flooding (day 60)	7.9	0.6	172050	0.22
Weak drought	Roundout +25% (small units)	5.5	-1.7	168150	0.15
Weak drought	Roundout +25% (large units)	2.1	-4.9	162750	0.25
Weak drought	Consistent flooding	-3.2	-9.8	154350	0.26
Weak drought	Active flooding (day 1)	-7.5	-13.8	147450	0.26
Strong drought	Active flooding (day 60)	2436	-81.5	31700	0.51
Strong drought	Active flooding (day 1)	2108	-83.9	27600	0.16
Strong drought	Active flooding (day 90)	2104	-83.9	27550	0.61
Strong drought	Consistent minimum flooding	800	-93.4	11250	0.73
Strong drought	Consistent flooding	124	-98.4	2800	0.96
Strong drought	Roundout +25% (large units)	44	-98.9	1800	0.89
Strong drought	Increased wetland management all types 25%	36	-99	1700	1.10
Strong drought	Roundout +25% (small units)	28	-99.1	1600	1.16
Strong drought	New easements +25% (small units)	20	-99.1	1500	0.87
Strong drought	New easements +25% (large units)	-4	-99.3	1200	1.04
Strong drought	Increased wetland management herbaceous 25%	-16	-99.4	1050	1.21

Figure V.23 Simulation results (all management methods) in the Mississippi Alluvial Valley (MAV) mallard model - overview

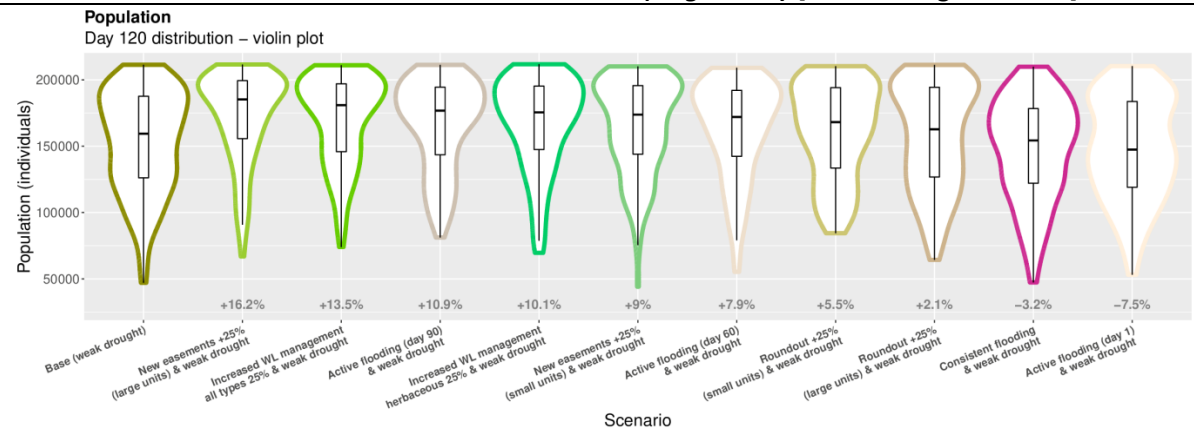
Standard conditions largest population at end of season: ***Active flooding (day 90)*** [Base +12.7%]



Flood conditions largest population at end of season: ***New easements +25% (small units)*** [Flood +0.9%]



Weak drought conditions largest population at end of season: ***New easements +25% (large units)*** [Weak drought +16.2%]



Strong drought conditions largest population at end of season: ***Active flooding (day 60) & strong drought*** [Strong drought +2436%]

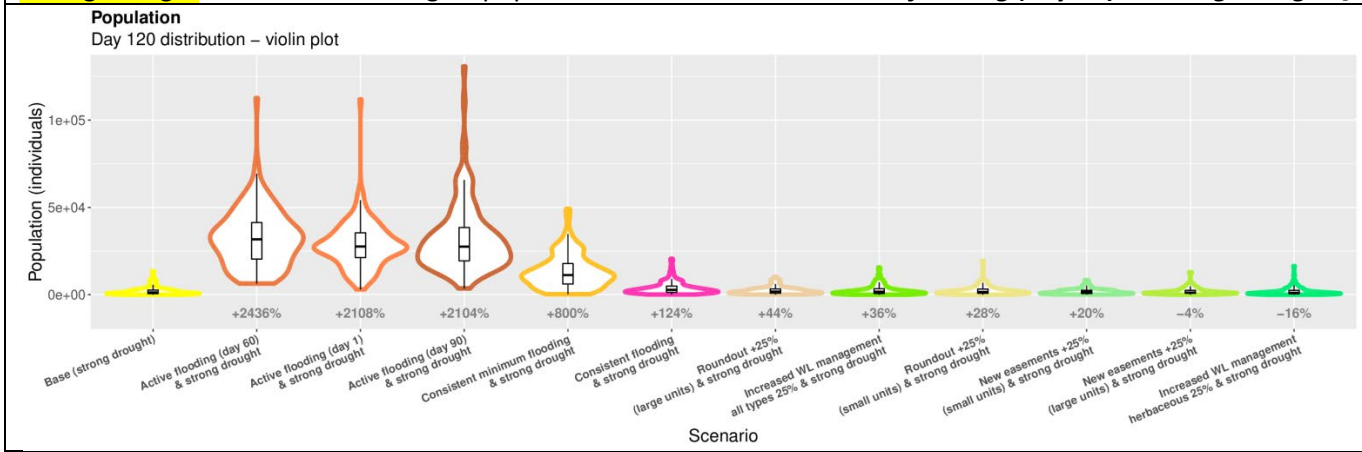
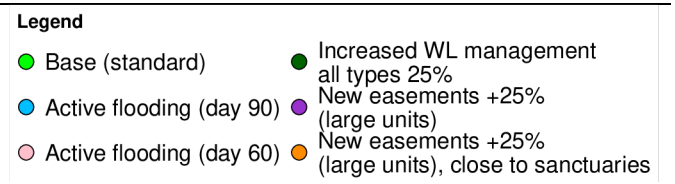


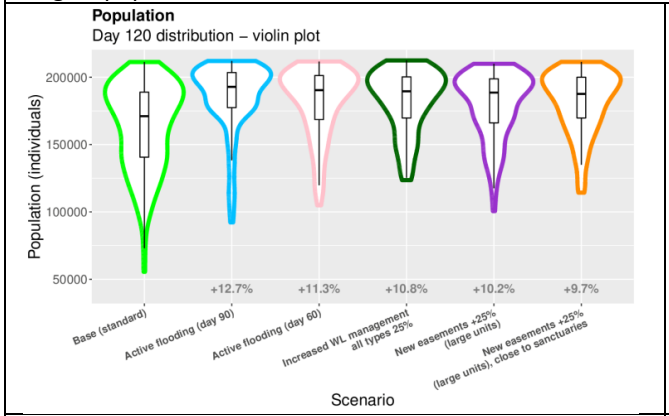
Figure V.24 Simulation results (all management methods) in the Mississippi Alluvial Valley (MAV) mallard model - **Standard** environmental conditions. The shaded areas represent bilateral 95% value ranges. WL is wetlands.

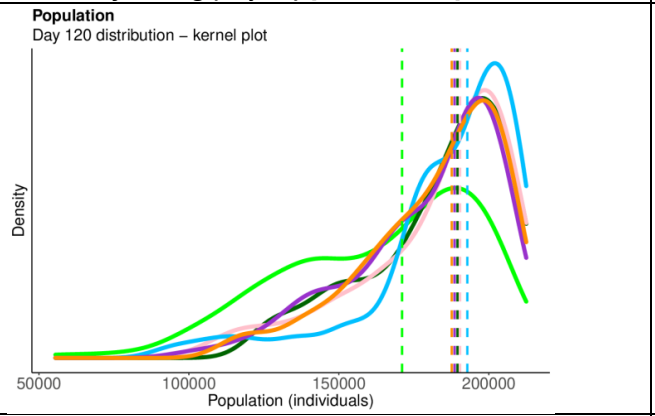
Subset – top five scenarios

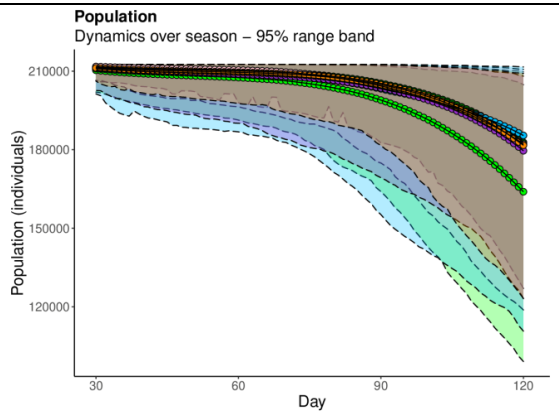
Scenarios: ● ***Increased wetland mgt. +25% (all types)*** ● ***New easements +25% (large units), close to sanc.*** ● ***New easements +25% (large units)*** ● ***Active flooding (day 60)*** ● ***Active flooding (day 90)*** ● *Base*

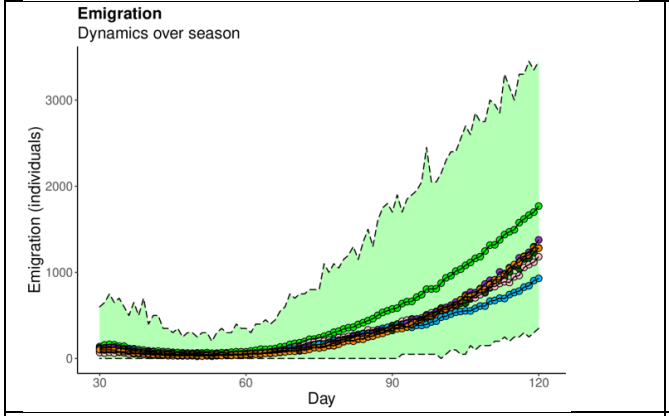
Largest population at end of season, under standard conditions: ***Active flooding (day 90)*** [Base +12.7%]

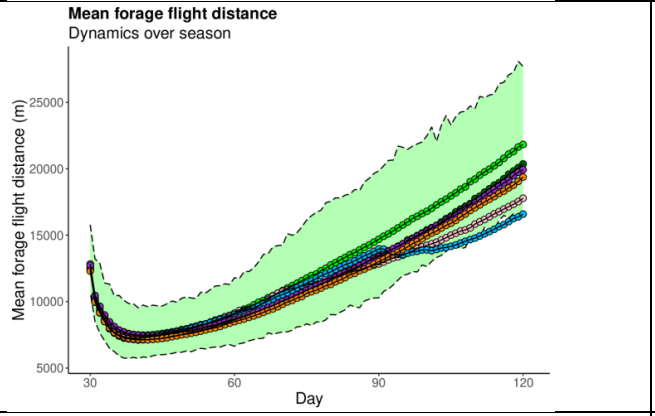


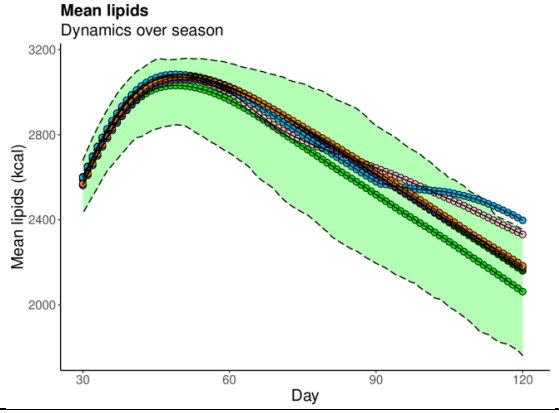


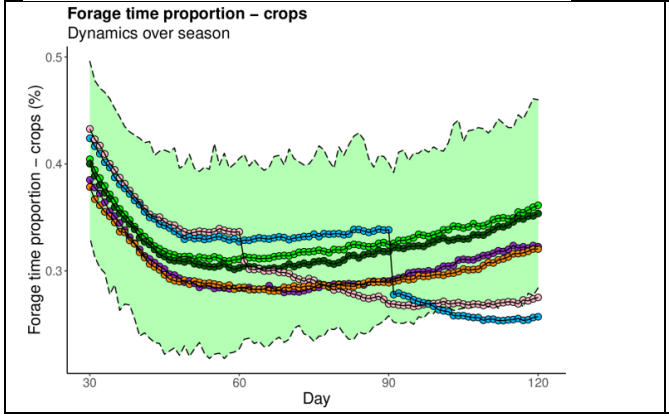


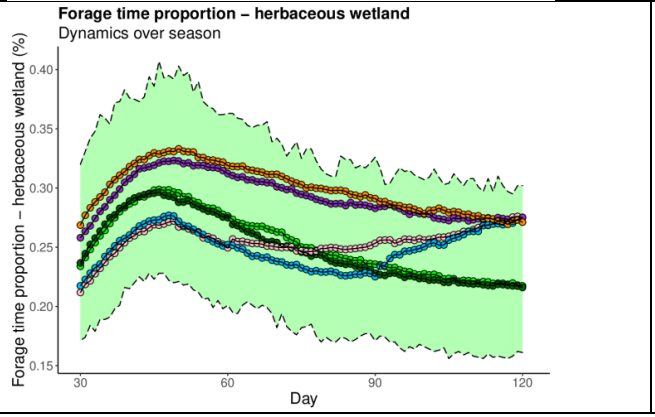












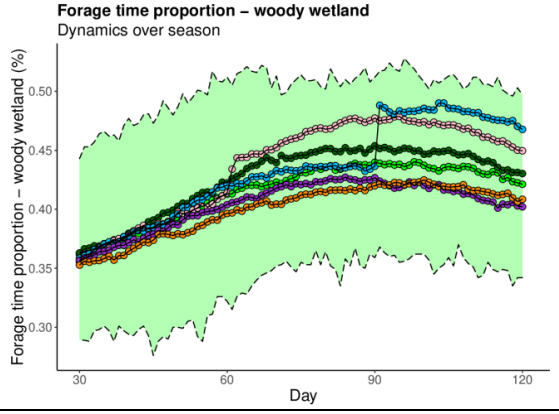


Figure V.25 Simulation results (all management methods) in the Mississippi Alluvial Valley (MAV) mallard model - **Flood** conditions. The shaded areas represent bilateral 95% value ranges. WL is wetlands.

Subset – top five scenarios

Scenarios: ***{ ● Increased wetland management +25% (all types) ● Roundout (large units) ● Roundout (small units) ● New easements (large units) ● New easements (small units) } & flood*** ● *Base (flood)*

largest population, under flood conditions: ***New easements +25% (small units)*** [Flood +0.9%]

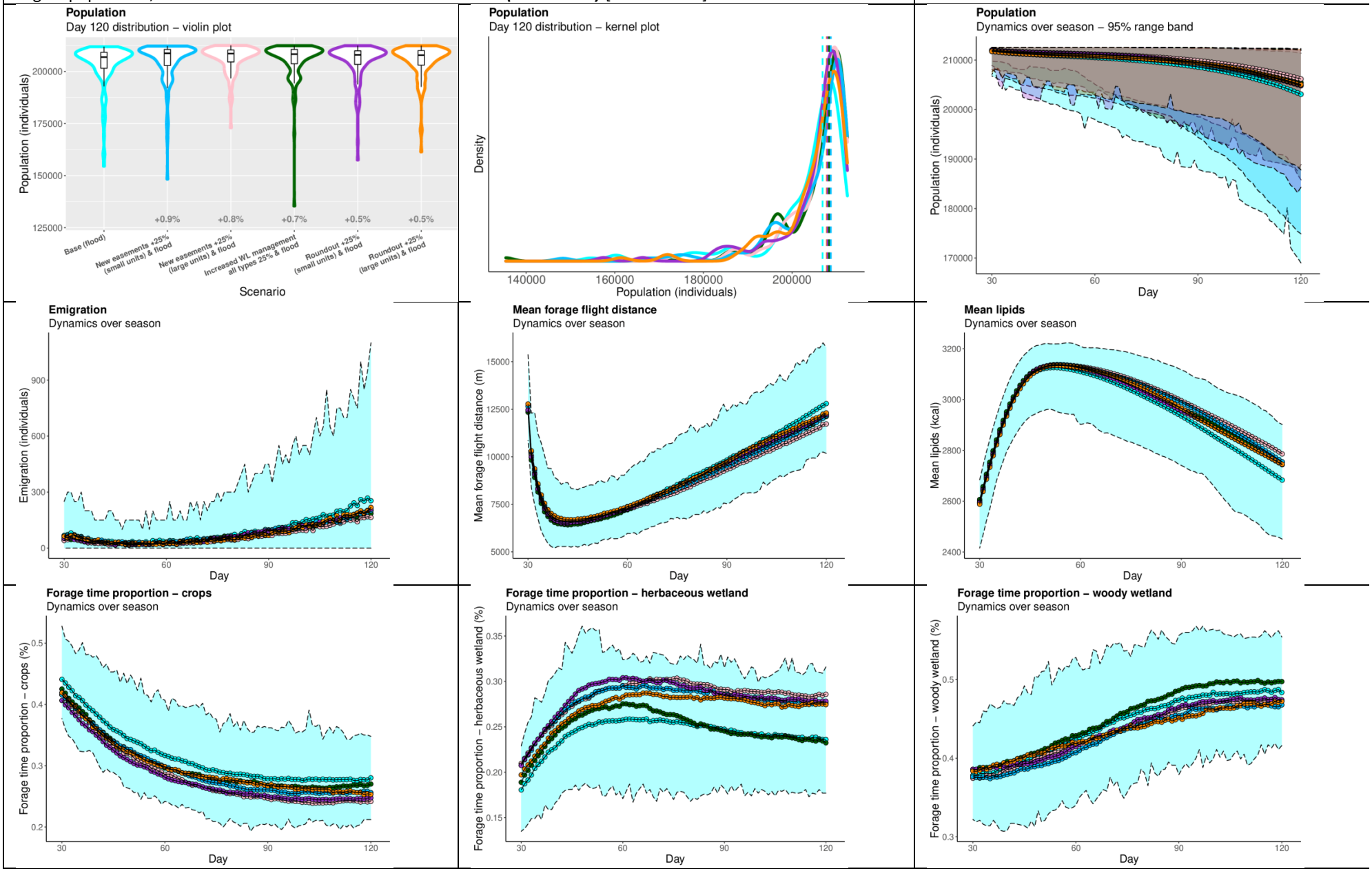


Figure V.26 Simulation results (all management methods) in the Mississippi Alluvial Valley (MAV) mallard model – **Weak drought** conditions. The shaded areas represent bilateral 95% value ranges. WL is wetlands.
Subset – top five scenarios
Scenarios: ***{ ● Active flooding (day 90) ● New easements +25% (small units) ● Increased wetland mgt. +25% (all types) ● Increased wetland mgt +25% (herbaceous) } & weak drought*** ● *Base (weak drought)*
largest pop., under weak drought: ***New easements. +25% (large units)*** [Weak drought +16.2%]

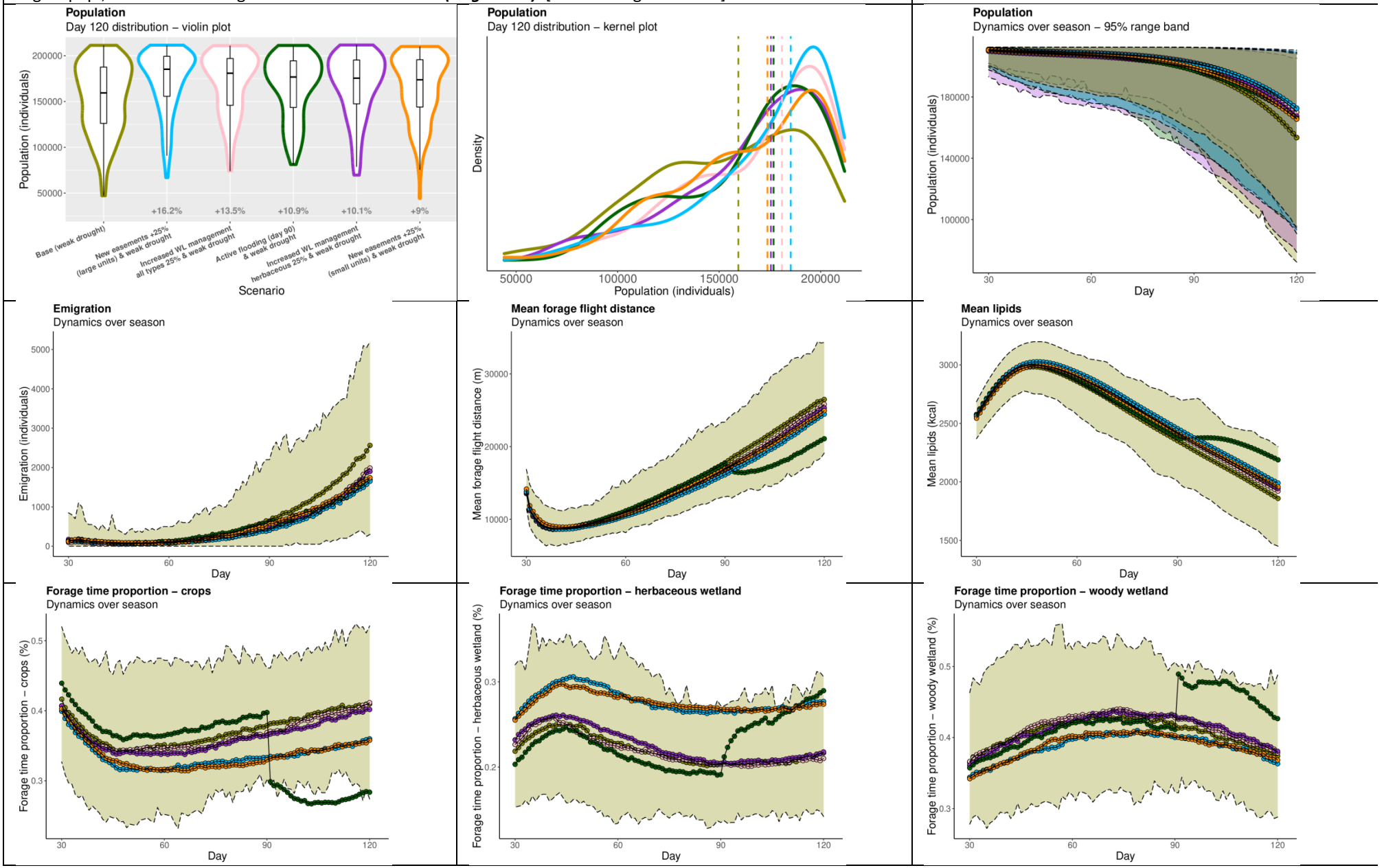
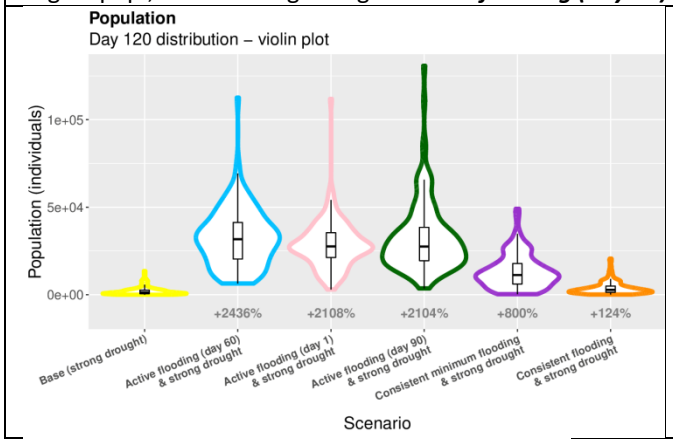
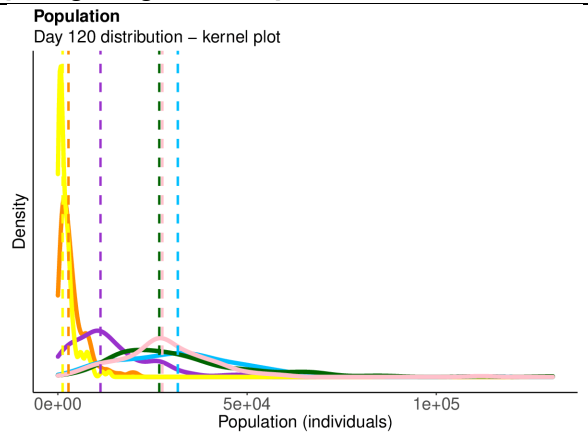
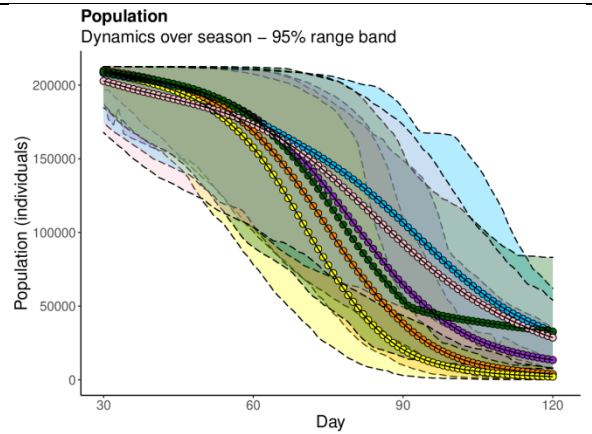
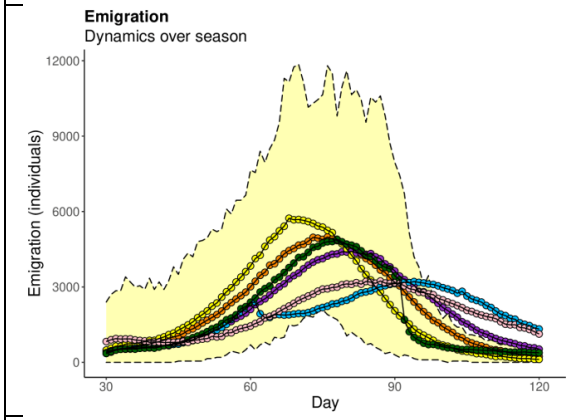


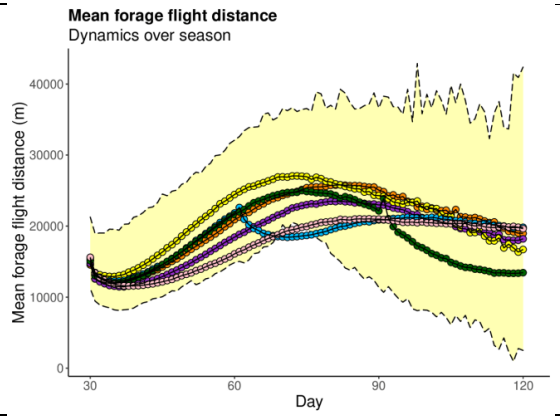
Figure V.27 Simulation results (all management methods) in the Mississippi Alluvial Valley (MAV) mallard model – **Strong drought** conditions. The shaded areas represent bilateral 95% value ranges.
Subset – top five scenarios
Scenarios: ***{ ● Active flooding (day 1) ● Active flooding (day 60) ● Active flooding (day 90)***
● Consistent flood ● Consistent minimum flood } & strong drought ***● Base (strong drought)***
largest pop., under strong drought: ***Active flooding (day 60)*** [Strong drought +2436%]

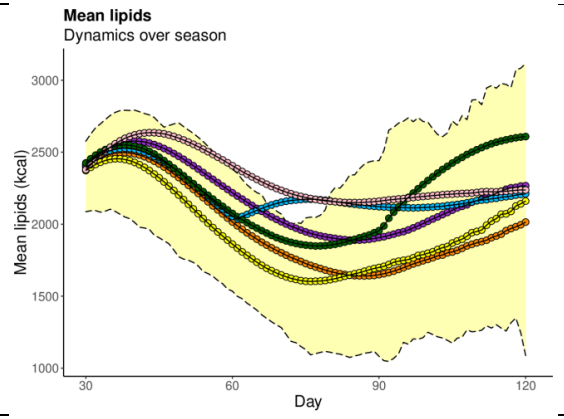


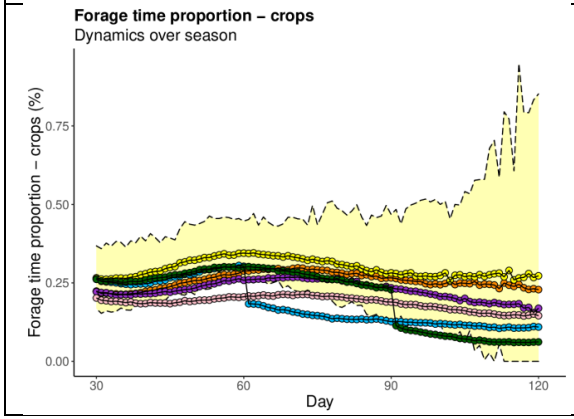


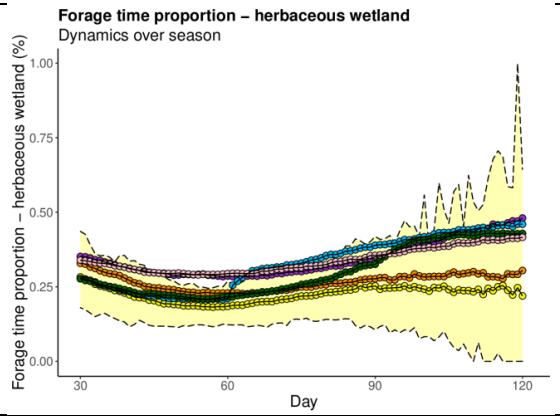


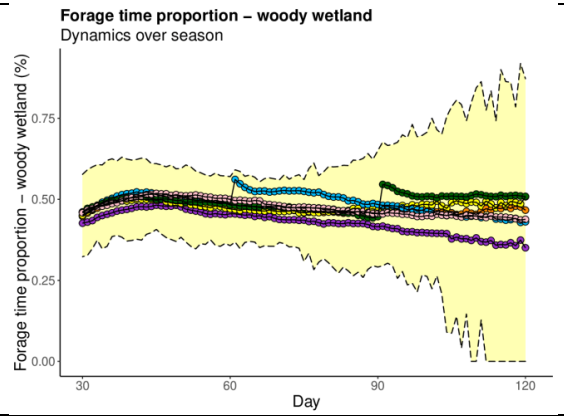


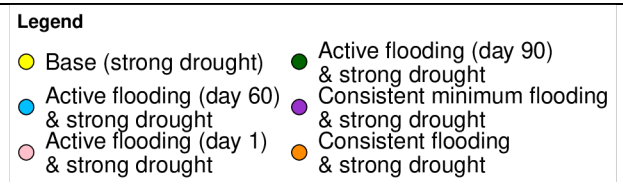












The top few scenarios under the different conditions were generally composed of enhanced management rather than increased area scenarios. Exceptions were the top scenario under weak drought conditions (a new easement scenario) and scenarios under flooding, where relative differences in population gain became so small that ranking was not informative. The top scenarios thus largely correspond to the groups discussed in detail in Results C. The best-performing increased area scenarios are discussed in Results D. For weak drought, strong drought, and flood conditions, no simulation runs of the selected location variants of increased area scenarios were carried out; thus, the omnibus comparison for these conditions is less extensive. However, the random location variants are included.

Under standard conditions (Figure V.24), the largest gain in mallard abundance among all scenarios occurred under the two late-season active flooding scenarios (day 60 and 90) , followed by increased wetland management [all types]. The most effective increased-area scenario was ranked fourth and yielded ~80% of the top scenario's gains. This was followed by a block of similarly effective new easement scenarios (that corresponded to the group shown in Figure V.12) and the day 1 active flooding scenario. Most roundout scenarios were ranked below these. The intensive management and consistent flooding scenarios yielded among the lowest gains (Figure V.23).

The highly ranked new easement scenarios showed somewhat different habitat use characteristics than the active flooding scenarios, as would be expected from their dissimilar temporal setups (fixed habitat availability in new easement scenarios vs substantial change in availability during the season in active flooding scenarios). At the start of the season, herbaceous wetland use in highly ranked new easement scenarios was at a level that was not achieved under active flooding (any time) scenarios until the very end of the season, and there was a concomitantly lower use of crops and woody wetlands throughout. In contrast, the other enhanced management scenario in the top five, increased wetland management [all types], had habitat use dynamics similar to the base scenario (Figure V.24 – lower panels). Nonetheless, each of these scenarios achieved a median population gain of at least 9.7% (16,550 mallards).

Under weak drought (Figure V.26), the top scenario (greatest increase in mallard abundance) was large new easements followed by increased wetland management [all types] and active flooding (day 90). Differences between these three scenarios were more pronounced than under standard conditions, with added gains of ~3% (~4,000 mallards) at each rank. Both roundout scenarios yielded much lower gains, and consistent flooding and active flooding (day 1) were the least effective (see Results II D for discussion). The same differences in habitat use as noted for standard conditions (above) were observed.

Under strong drought (Figure V.27) the active flooding scenarios yielded very substantial gains in abundance; consistent minimum flooding was less effective but still produced noticeable gains. In contrast, all increased area scenarios produced only marginal effects on abundance gains, and thus do not constitute viable alternative management approaches under strong drought. For flooding conditions (Figure V.25), there was no scenario or group of scenarios that yielded conspicuous improvements over base conditions.

The principal difference between the enhancement scenarios and the area increase scenarios was that the former acted in the closely circumscribed areas of existing easements and created relatively abundant forage biomass reservoirs: the increased/intensive management variants created managed (77.6 g/m^2) or intensively managed (103 g/m^2) herbaceous wetlands, while the flooding variants mostly activated unmanaged (42.8 g/m^2) herbaceous wetlands. In contrast, the increased area

scenarios added the relatively less abundant reservoirs of restored wetlands (33.1 g/m^2) in parcels that were distributed over a wider area. Total food energy gain was always greatest for the active flooding scenarios (under standard conditions, 3.7×10^9 kcal), followed by the new easement scenarios (~2×10^9 kcal); the increased wetland management scenarios added much less food energy than any increased area scenario, including roundouts ($0.2–0.4 \times 10^9$ kcal). This, however, did not translate directly into ranking by population gains. Under the more common environmental conditions (standard and weak drought), increased wetland management performed much better than would be expected from its food energy yield, being among the top three scenarios both times. This suggests that enhancing the durability and reliability of a small selection of existing food sources could be more efficient than adding a numerically greater amount of more readily depleted or unreliable sources (as happened in both active flooding and increased area scenarios) – the "abundant reservoirs" approach. Note that it is probably possible to take this philosophy too far, as suggested by the comparatively poor performance of the very localized intensive wetland management scenario (see Results D).

However, the benefits to mallards of new easement additions (but not of roundouts) compared well to both active flooding and increased wetland management under standard conditions. Under weak drought conditions, random new easement placement in large units even outperformed both of these enhancement types. There is no obvious explanation for why this scenario was particularly favorable under weak drought. However, the fact that the small unit variant, which had essentially identical metric dynamics, ranked considerably lower (Figure V.26) again suggests a combined effect of enhancing patches, cohesiveness of enhanced areas, and increased map accessibility, that under weak drought was more beneficial in the aggregate than only enhancing cohesive patches. Regardless, the substantial yields from new easement scenarios indicate that the distributed addition of newly restored wetlands would also constitute an effective approach. It should be noted that the comparatively poor performance of roundout scenarios largely depended on the fact that patches added in roundout, in contrast to new easement establishment, were not filtered to conform to the observed higher proportion of crops vs existing wetlands in current easements (~69% : 31%) and thus provided fewer restored wetlands and consequently lower energy gains and fewer instances of slow-decaying wetland food reservoirs (see Methods III C). We do however suggest that this parameterization is probably a realistic reflection of the difference between the two types of easement enlargement, as the process of rounding out existing easements would give less opportunity for choosing parcels of suitable habitat composition.

The frequent lack of correlation between gross amount of biomass added to the landscape in management scenarios and gain in end-of-season mallard population suggests that the distribution of biomass on the landscape (e.g. clustering of patches, or presence in few abundant versus multiple scarcer biomass reservoirs) was often equally as or more important than the total amount of biomass. Studies have shown that dabbling duck abundance in wintering areas can be highly associated with specific combinations of different foraging opportunities (e.g. flooded crops and moist-soil wetlands) that allow switching between food sources under changing conditions such as late-season food depletion (Herbert et al. 2021). Landscape-level energy metrics such as those often employed in duck energy day (DED) models are unlikely to detect these relationships. For example, in the "absence of easements" scenario under weak drought conditions, population abundance declined by 80% due to unfavorable reductions in abundant food reservoirs (V. Scenario results – A. Absence of easements/management in easements), however a simple landscape energy metric such as days to deficit predicted that the starting population could be sustained by existing biomass for more than three years.

In summary, the results suggest that the effects of management approaches on mallard populations that were simulated here will only be observed under what we have termed standard (i.e., average) or moderately lower inundation conditions. There is little indication that even intensive management approaches will make a substantial difference under extreme conditions like those that exist in a high-flood or strong drought season. The exception was the active flooding approach under strong drought conditions, which showed a capacity for considerably increasing carrying capacity. Under standard conditions, the partial active flooding of easements later in the season and upgrading of unmanaged wetlands to managed status provided the best results. Scenarios that enhanced the quality or availability of wetlands in existing easements generally yielded greater gains in end-of-season population abundance than scenarios that added new easement area with restored wetlands, but benefits from the latter were still sizeable. If new easement areas were added, establishment of entirely new easements with a high percentage of converted crop patches was preferable over rounding out existing easements using any directly contiguous patches. Selecting added easement patches based on proximity to sanctuaries or former wetland character enhanced the effectiveness of roundouts but was largely ineffective for new easements.

Although we estimated population abundance gains or losses in the form of mallard numbers and percentages, these results are meant to be interpreted as relative differences among populations rather than absolute population numbers. It should be noted that the outcomes provided represent median values that provide an approximation of the most common result across an often wide range of potential end-of-season outcomes (these ranges are provided in results tables as well as figures, in the form of CVs and bilateral 95% value ranges). In addition, the potential ranges of input values should also be kept in mind. While such distributions were modeled with regard to food availability and inundation probabilities, we used a single fixed value for the abundance of the immigrating mallard population, representing the area-scaled median of Arkansas Mid-Winter Count numbers for the period 1981-2016. Over this period, this number has varied annually by up to approximately ±90% (USFWS 2016), and it is to be expected that actual populations in the region may be much larger or smaller than the modeled ones in any given year, with consequently changed landscape exploitation patterns and emigration behavior.

Due to limitations in current knowledge about behavioral and ecological processes (particularly at the level of the individual) and limited data availability, the model contains many approximations and simplified representations; these are discussed in the Methods section. Changes in our understanding of these factors will affect the outcome of future modeling attempts of the populations simulated here. For example, the absence of representations of seasonal changes in mallard behavior and physiology in this model prevented the increase in lipid stores that would be expected in the period leading up to spring migration. Processes related to hunting and its effects on direct mortality and duck behavior are likely to be particularly impactful. Representations of hunting were not part of the present model because it was not possible to implement a sufficiently responsive mechanism during development. Studies have found that in the modeled region, hunting made up the overwhelming majority of wintering mallard deaths, while mortality from other causes was rare to almost absent (Reinecke, Shaiffer, and Delnicki 1987; Dugger, Reinecke, and Fredrickson 1994; Link 2007). Consequently, the present model (lacking hunting) did not consider mortality and focused on emigration as the main mechanism of changes in population size over time. In reality, mortality from seasonal hunting would reduce population numbers throughout the mid-section of the simulated time period (December and January). Furthermore, hunting disturbance is known to strongly influence behavioral patterns of ducks, leading to avoidance of heavily hunted areas as well as prioritization of safe foraging and roosting locations (Dooley et al. 2010a, 2010b; Lancaster et al. 2015). Although there are

indications that sanctuary site location is not highly explanatory of dabbling duck distribution in the MAV (Pearse et al. 2012), hunting would be expected to enhance the importance of unhunted areas (sanctuaries) and of spatial configuration of easements relative to sanctuaries. In the simulated scenarios, these relationships might translate into increased importance of the "close to sanctuaries" variants of new easement and roundout scenarios, and possibly of roundout scenarios in general. The implementation of hunting-related processes is the next step in the planned further development of the Spatially-explicit Waterbird Agent-based Modeling Program (SWAMP) model, and we hope to be able to address this question in the future.

Acknowledgments

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