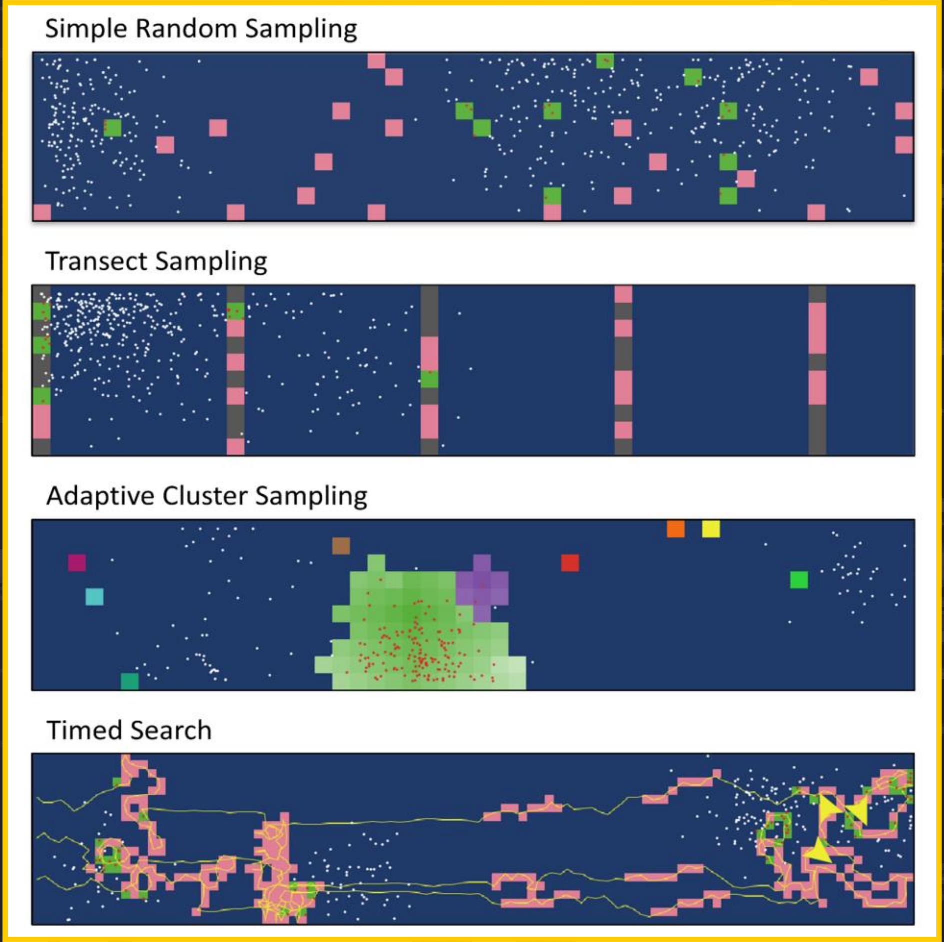
SAMPL: AN AGENT-BASED MODEL TO EVALUATE SPATIAL SAMPLING STRATEGIES

Kiara C. Cushway, Iris R. Foxfoot, Rachel R. Rosenberg, Astrid N. Schwalb, David R. Smith, and Todd M. Swannack

15th October 2025



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WHAT MAKES RELIABLE SAMPLING STRATEGIES SO IMPORTANT?

- True population characteristics are rarely known or realistically identifiable, but to conserve and manage populations, we need to be able to quantify them
- Resources like time and money are in limited supply
- Population estimates guide conservation actions

Poorly designed surveys → Inaccurate or Imprecise estimates → Inefficient or ineffective conservation/ management

Photo credit: Kiara Cushway

WHAT MAKES OBTAINING RELIABLE POPULATION METRICS CHALLENGING?

An ideal sampling technique would maximize efficiency and minimize bias, but in reality:

- Time and funds are limited
- Organisms vary in detectability, rarity, and spatial distribution
- All sampling strategies come with trade-offs
    - Random sampling may perform poorly for rare/clustered populations
    - Quantitative methods are often time consuming
    - Qualitative methods are inherently biased

On top of these: How can we evaluate the accuracy and precision of population estimates if we don't know the characteristics of the true population to begin with?

Photo credit: Woolnough Lab, Central Michigan University

Photo credit: Meghan Martinski

Grand et al. 2007; Strayer and Smith 2003

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Solution: Agent based modeling

Photo credit: Woolnough Lab, Central Michigan University

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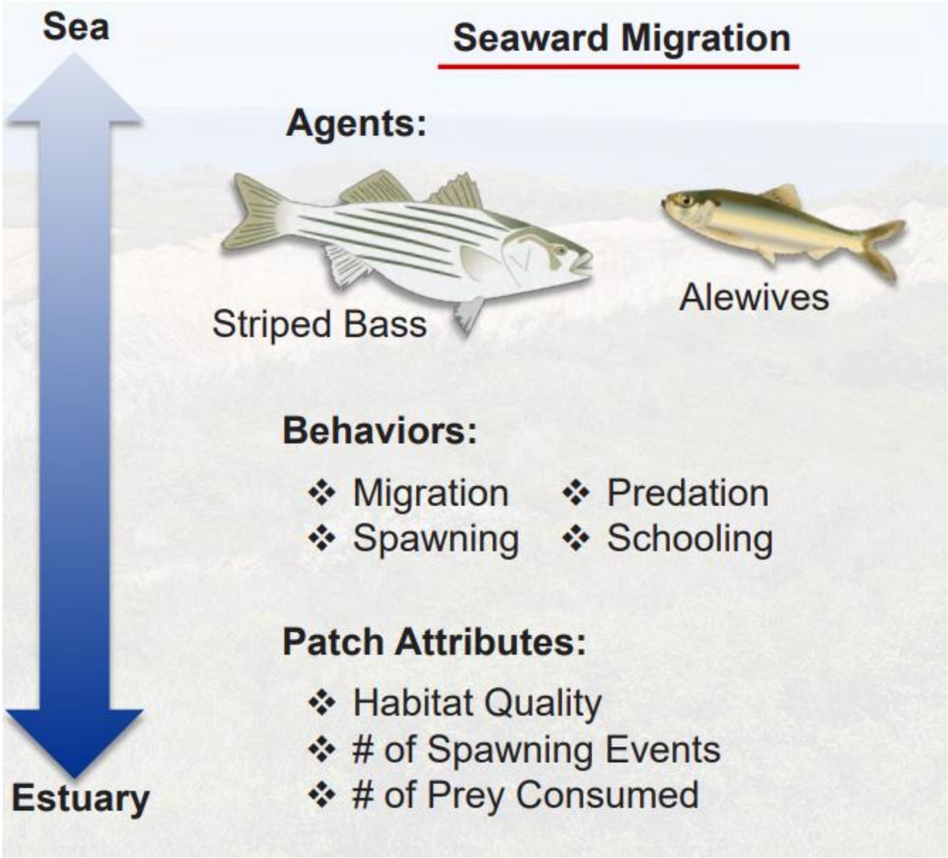
Grand et al. 2007; Strayer and Smith 2003

WHAT THE HECK IS AGENT-BASED MODELING?

- Flexible modeling approach
- ‘Agents’ interact with each other or their environment
- Behavior is controlled by formal equations or decision rules

NetLogo:
- Free, open-source modeling platform
- Mobile agents called ‘turtles’ interact with each other or with stationary agents called ‘patches’
- Graphical user interface + code



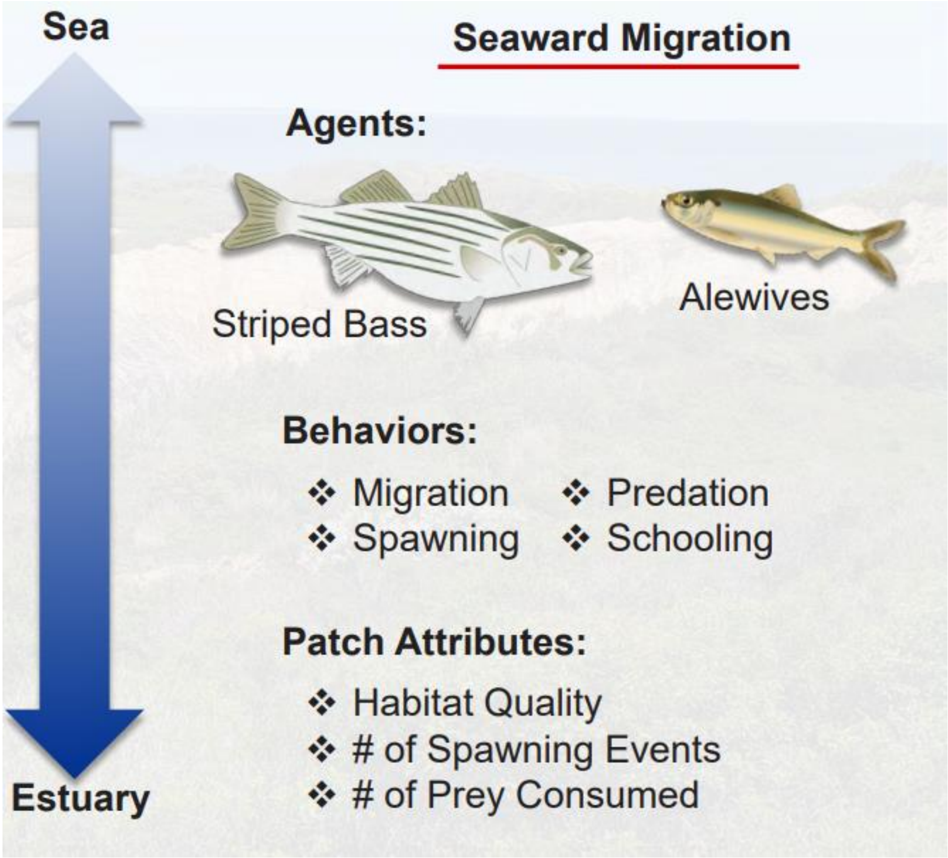
Credit: Quintana et al. (2024); NextGen Seminar

Wilensky 1999; Helbing and Balietti 2012; Swannack et al. 2025

WHAT THE HECK IS AGENT-BASED MODELING?

NetLogo models have been used to simulate:

- Fish behavior during migration



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WHAT THE HECK IS AGENT-BASED MODELING?

NetLogo models have been used to simulate:

- Fish behavior during migration
- Disease dynamics in aquaculture settings

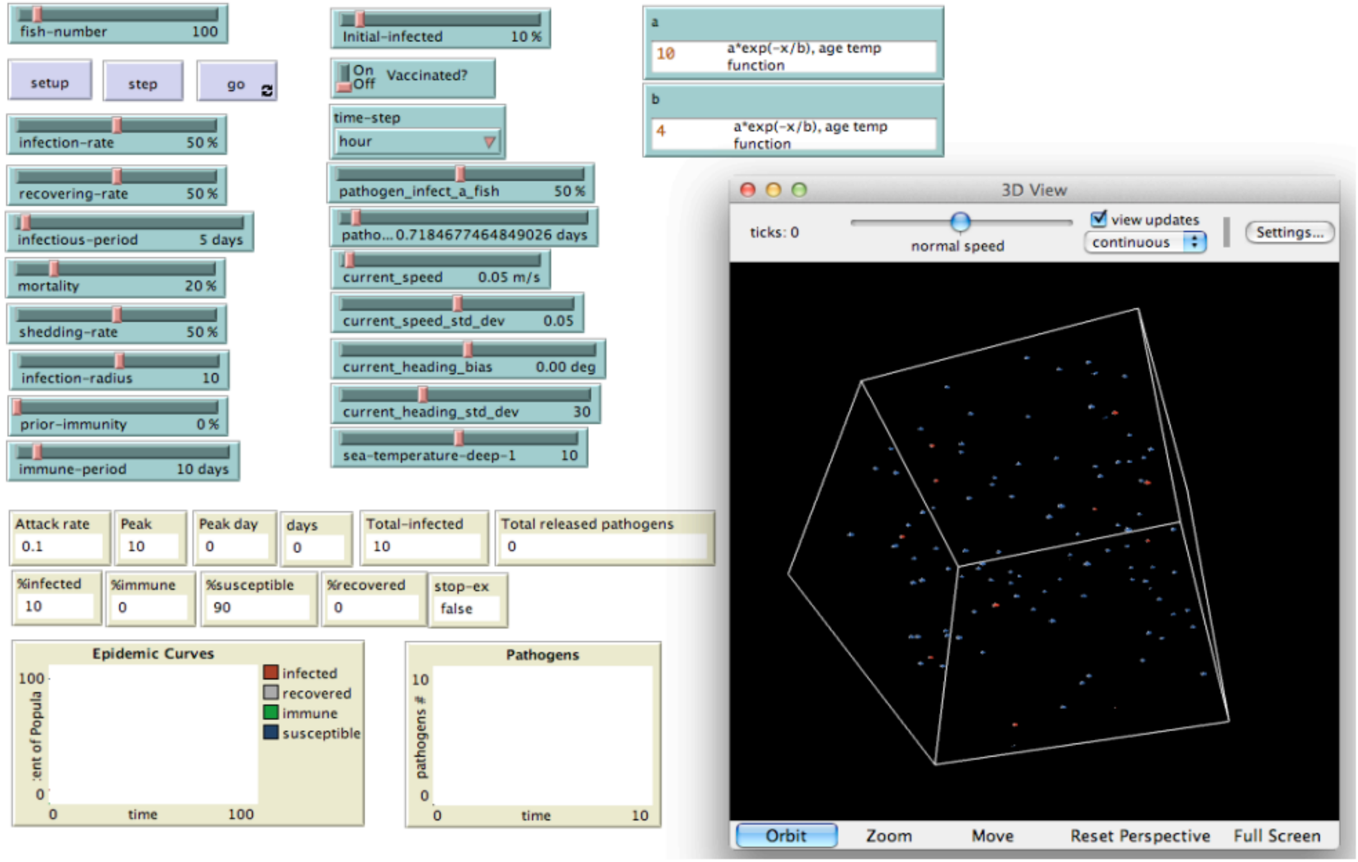


Figure 10. Graphical user interface (GUI) developed for the model implementation

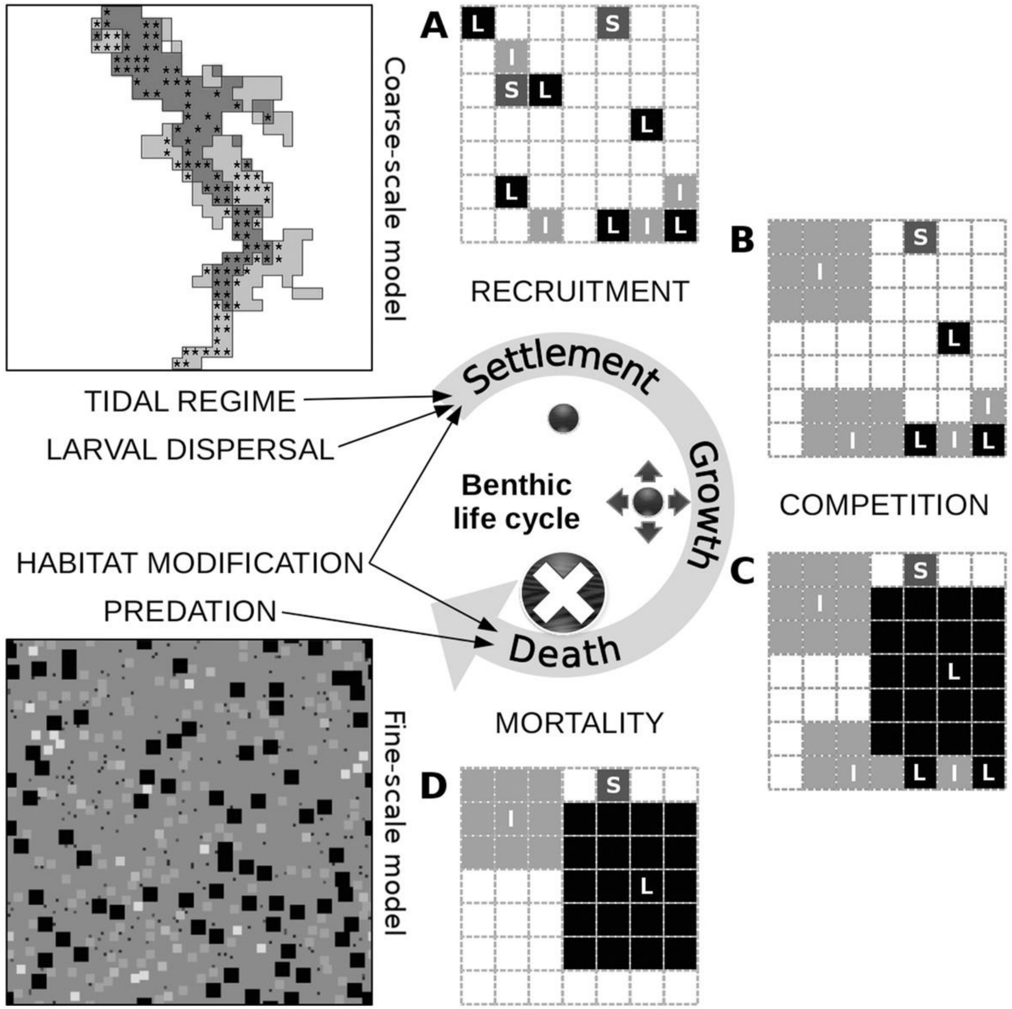
Credit: Alaliyat and Yndestad (2015); Figure 10

Wilensky 1999; Helbing and Balietti 2012; Swannack et al. 2025

WHAT THE HECK IS AGENT-BASED MODELING?

NetLogo models have been used to simulate:

- Fish behavior during migration
- Disease dynamics in aquaculture settings
- Community dynamics of marine benthic macroinvertebrates



Credit: Alexandridis et al. (2018); Figure 2

Wilensky 1999; Helbing and Balietti 2012; Swannack et al. 2025

WHAT THE HECK IS AGENT-BASED MODELING?

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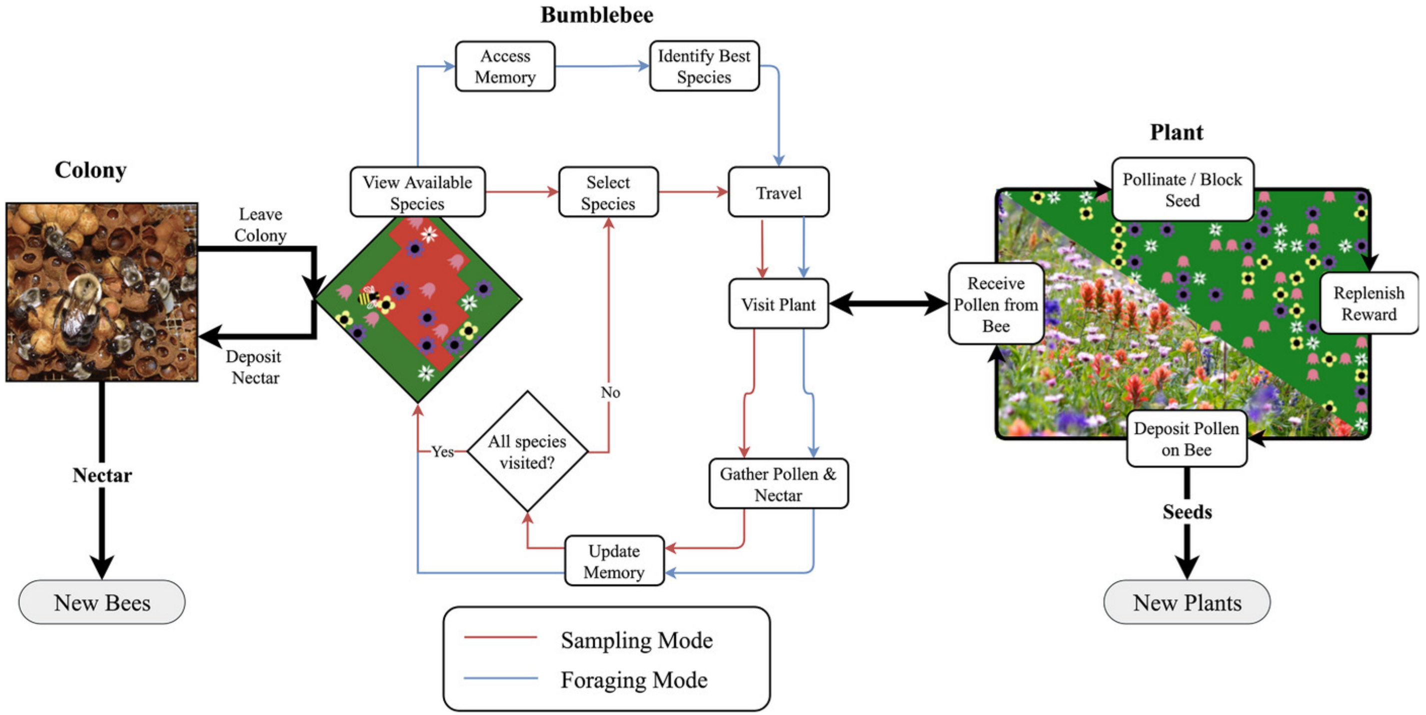
- Fish behavior during migration
- Disease dynamics in aquaculture settings
- Community dynamics of marine benthic macroinvertebrates
- Pollination patterns of bees

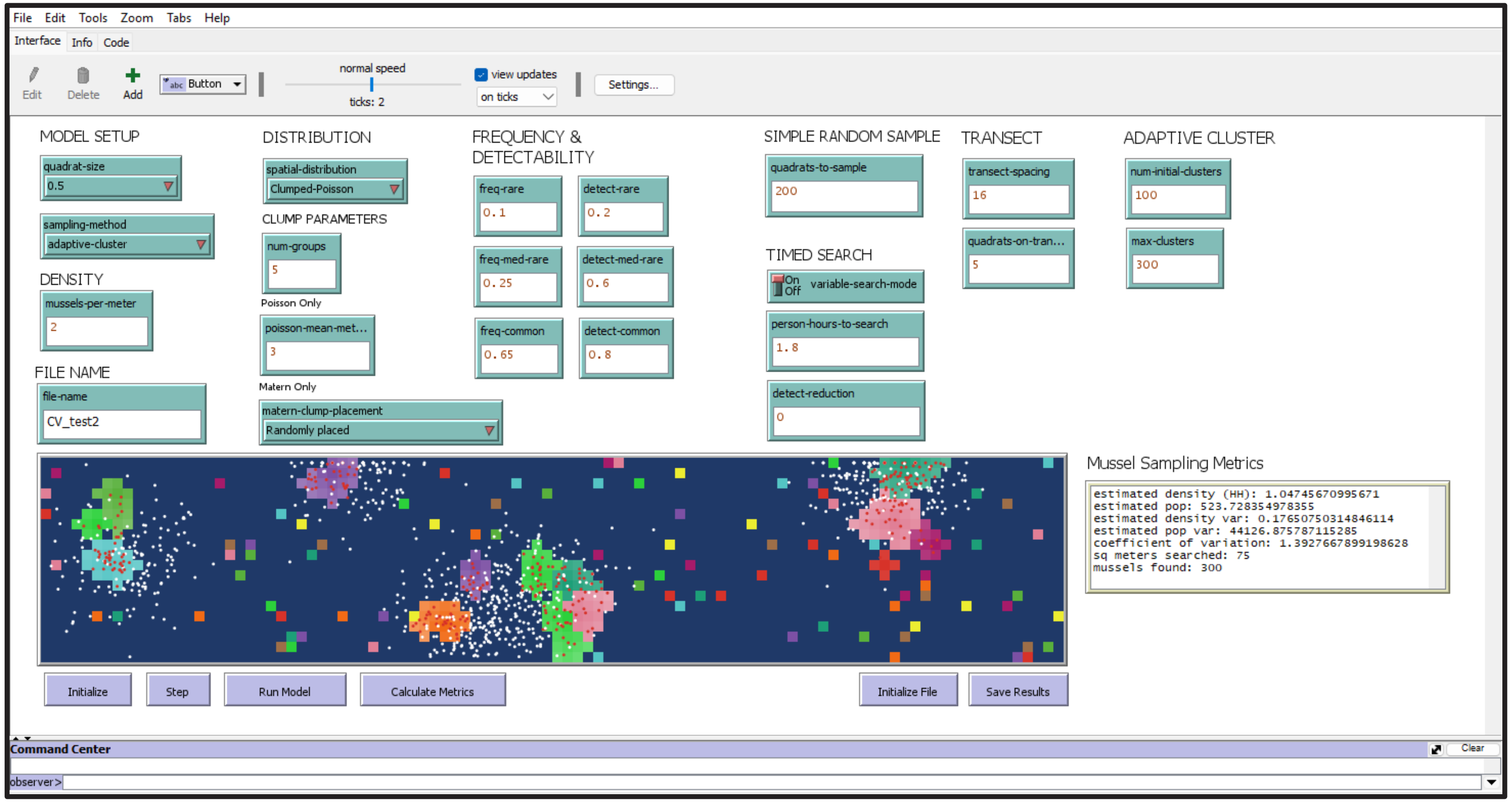


Credit: Gegear et al. (2021); Figure 1

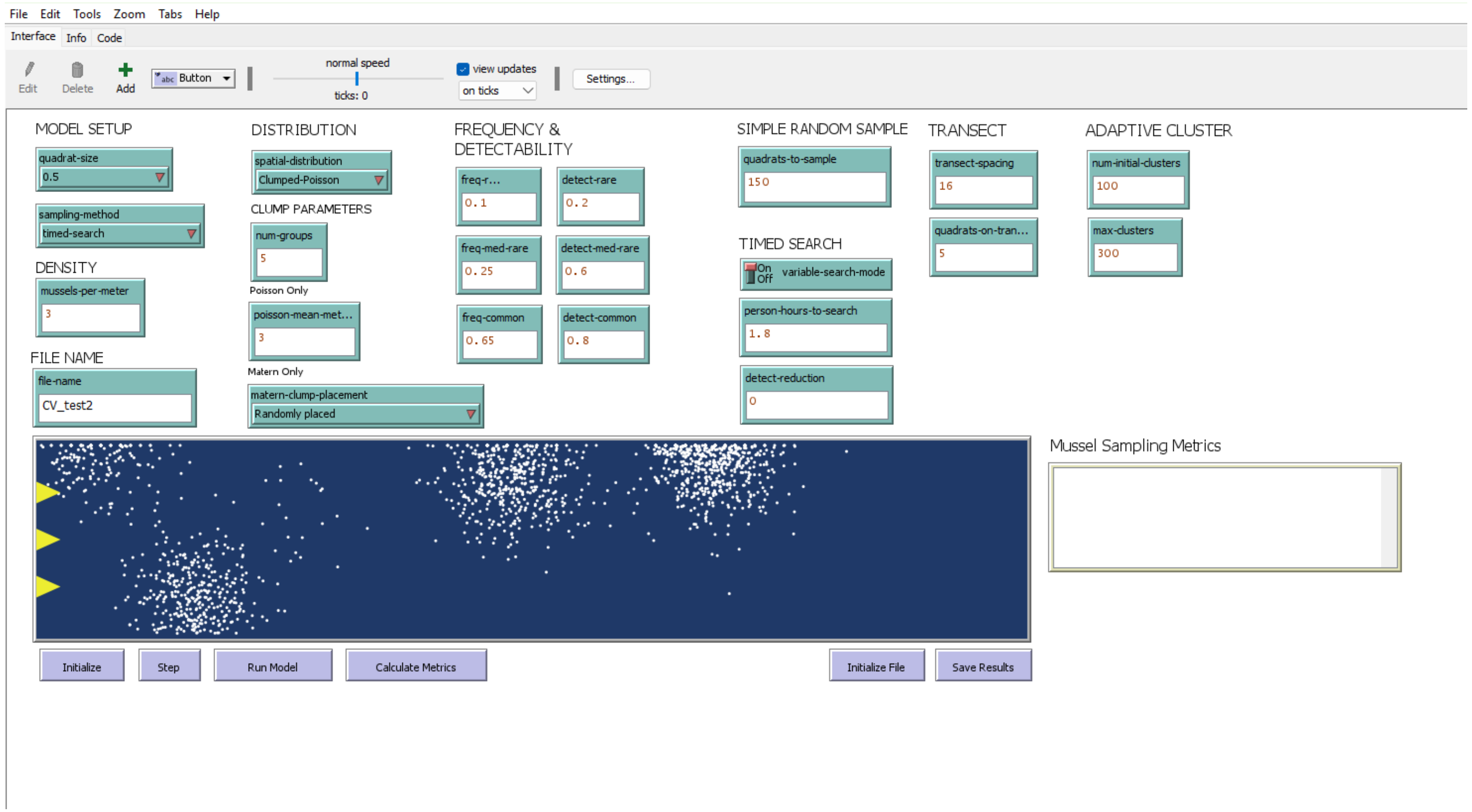
Wilensky 1999; Helbing and Balietti 2012; Swannack et al. 2025

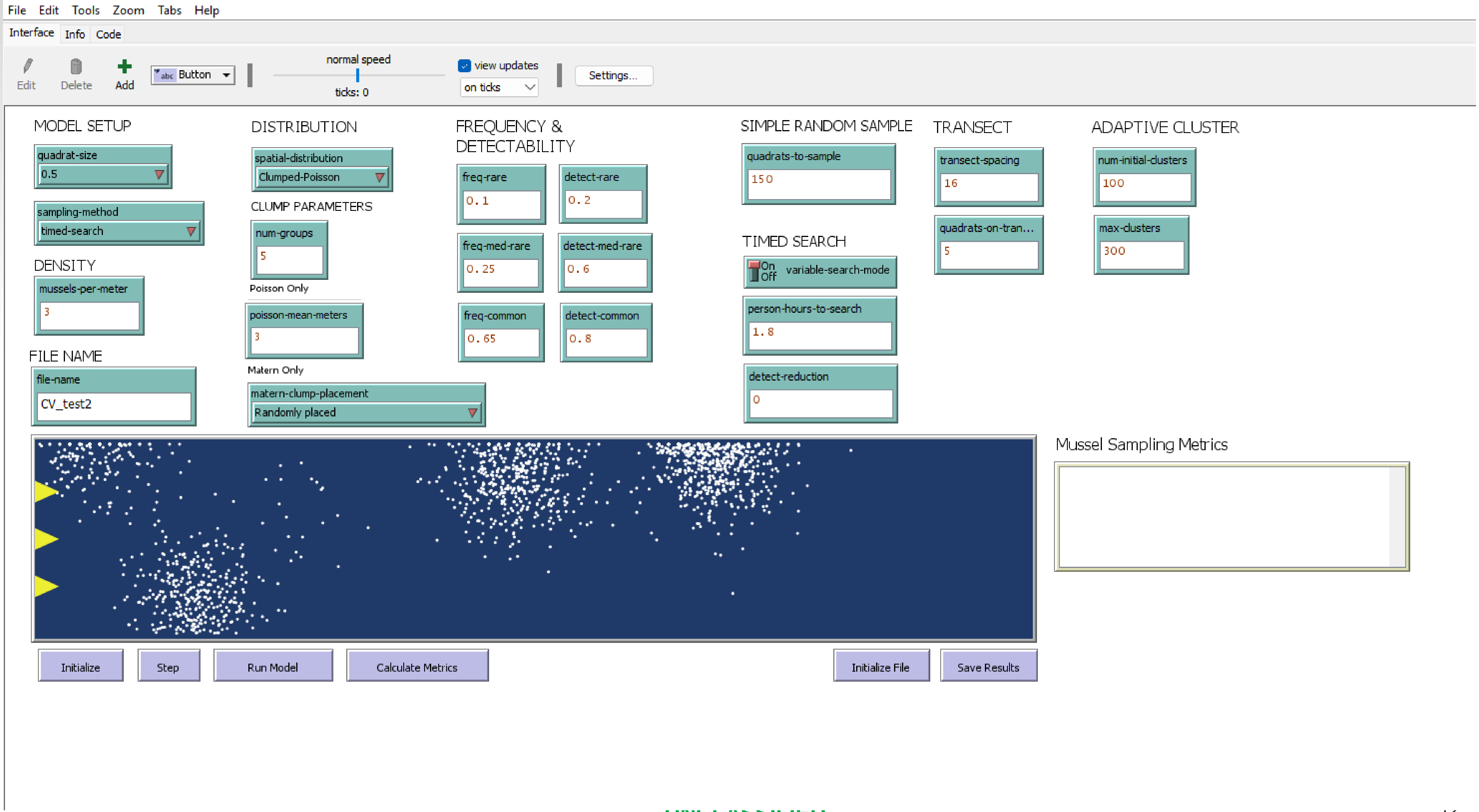
INTRODUCING SAMPL: AN AGENT-BASED MODEL FOR SIMULATING SAMPLING METHODS

- "**S**urvey **A**nalysis for **M**onitoring **P**opulation **L**evels"
- Flexible model for simulating sampling schemes
- Designed to simulate both quantitative and qualitative sampling



THE NITTY GRITTY: BREAKING DOWN SAMPL'S CAPABILITIES

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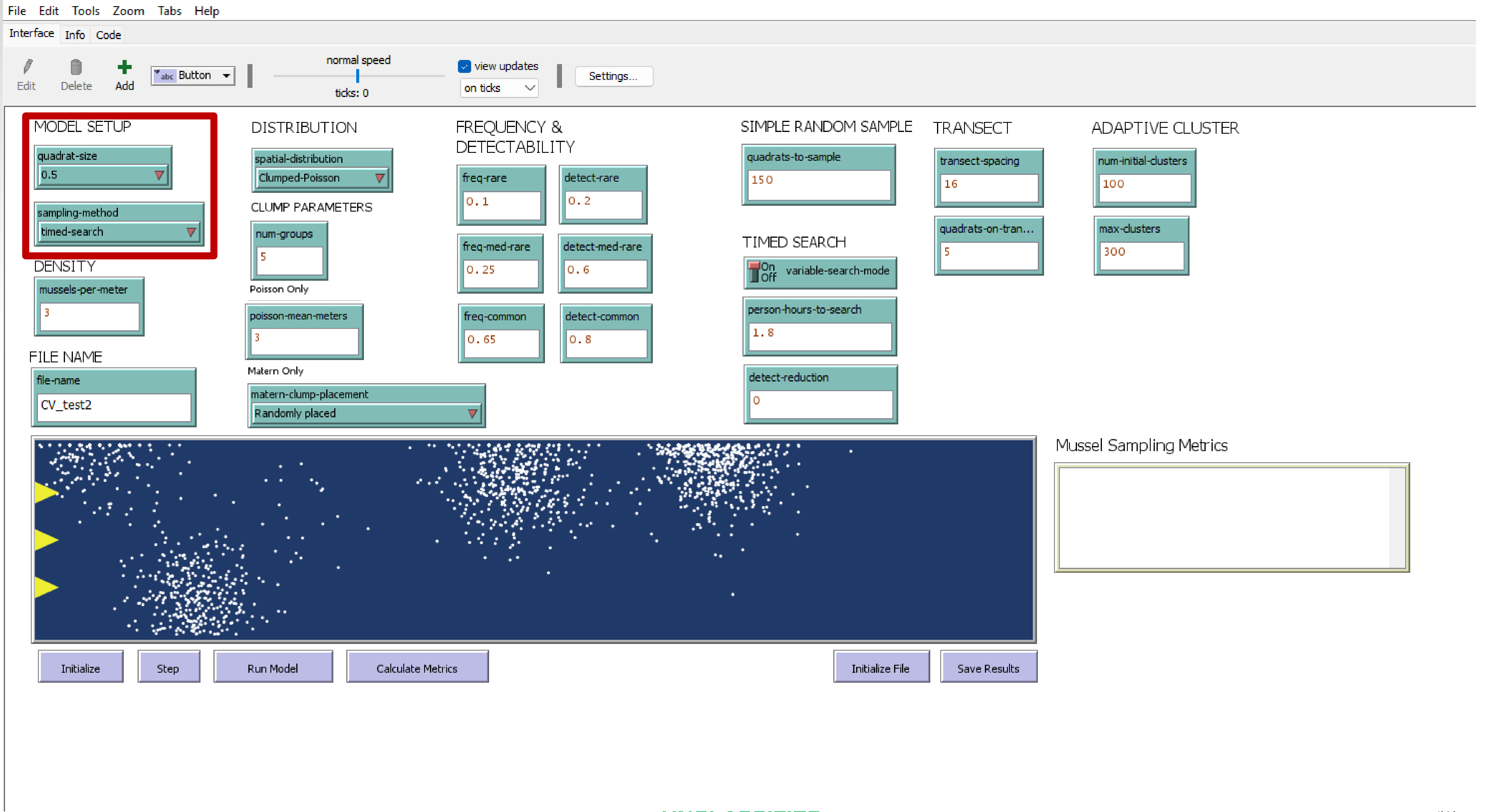
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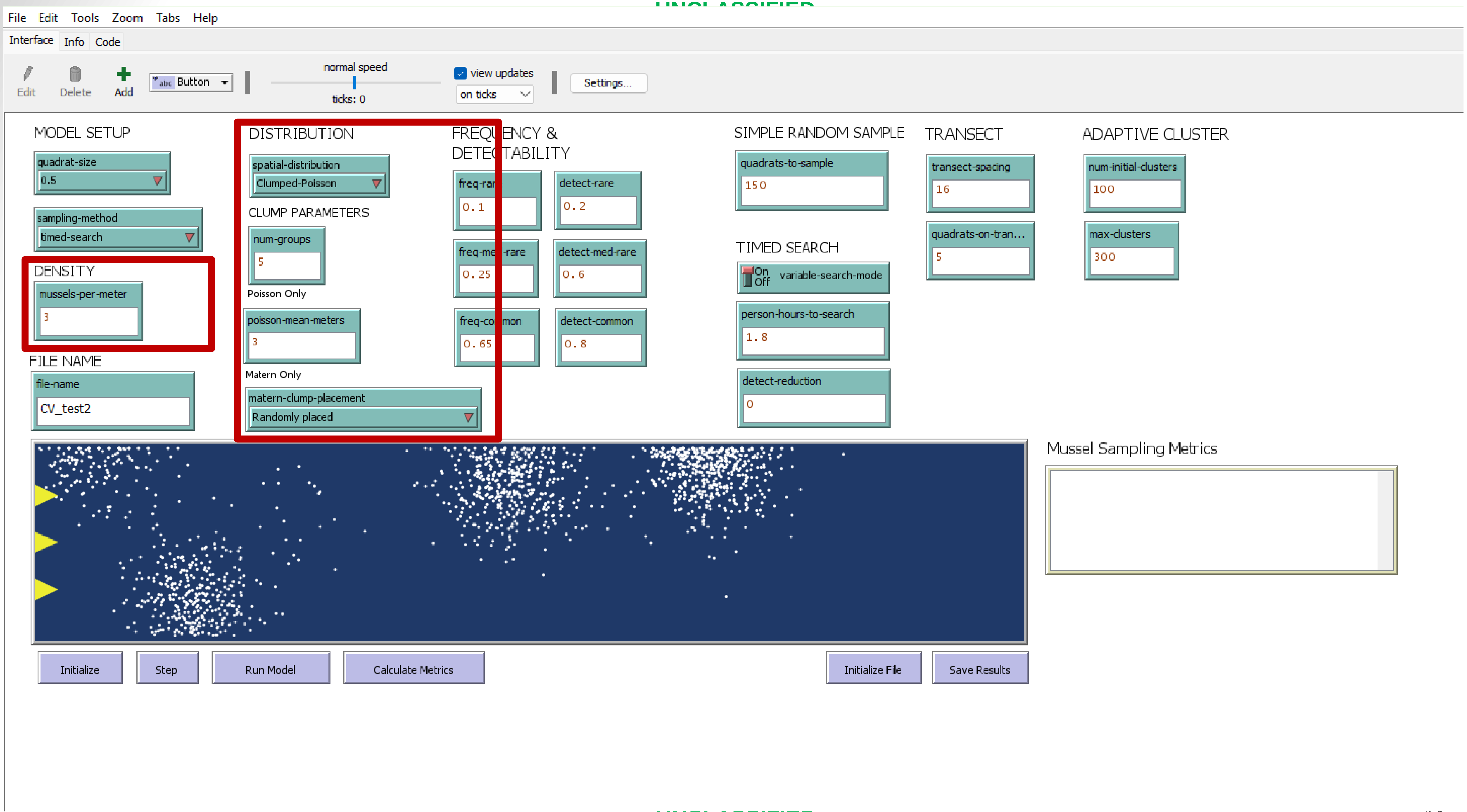
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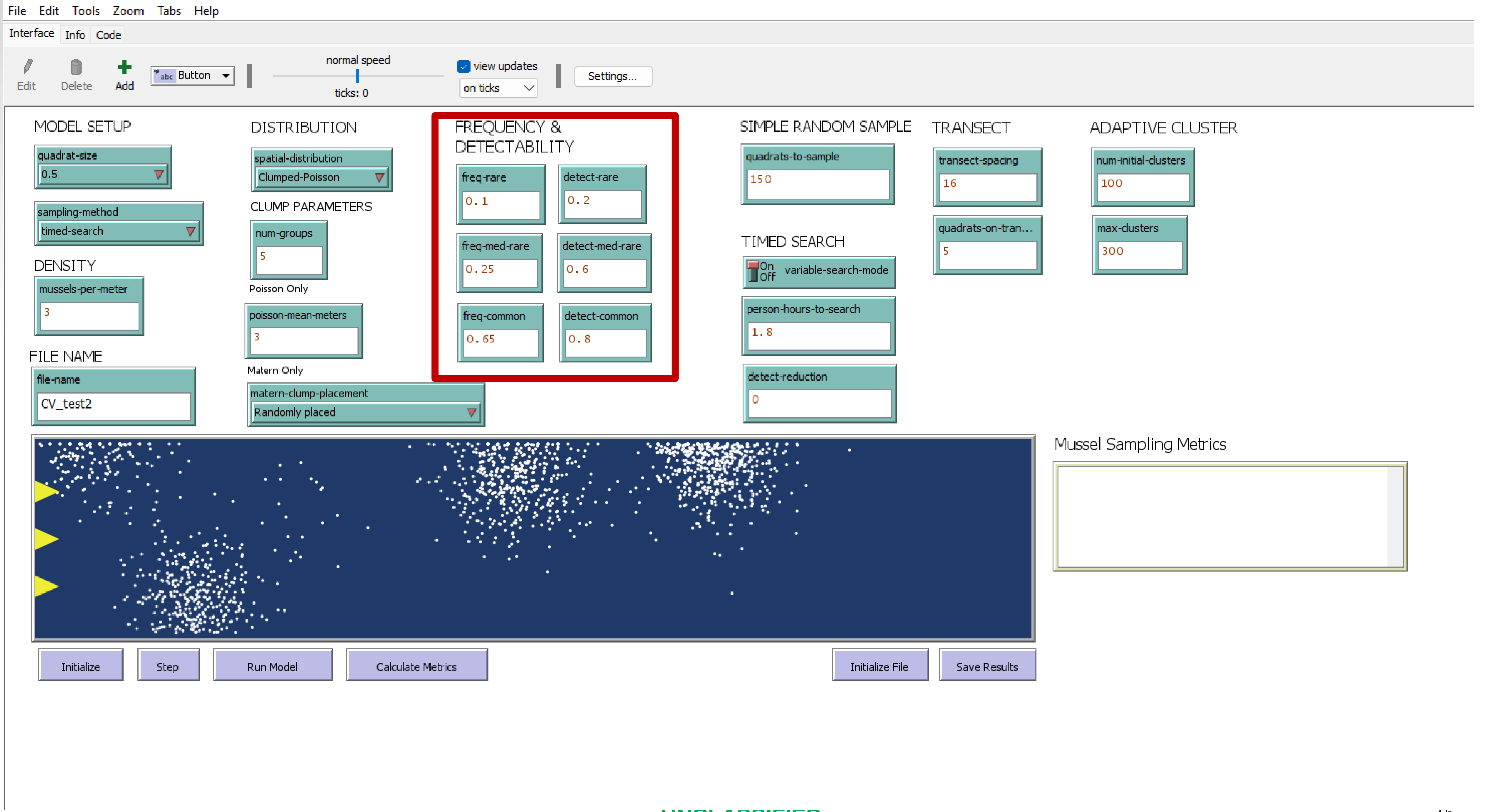
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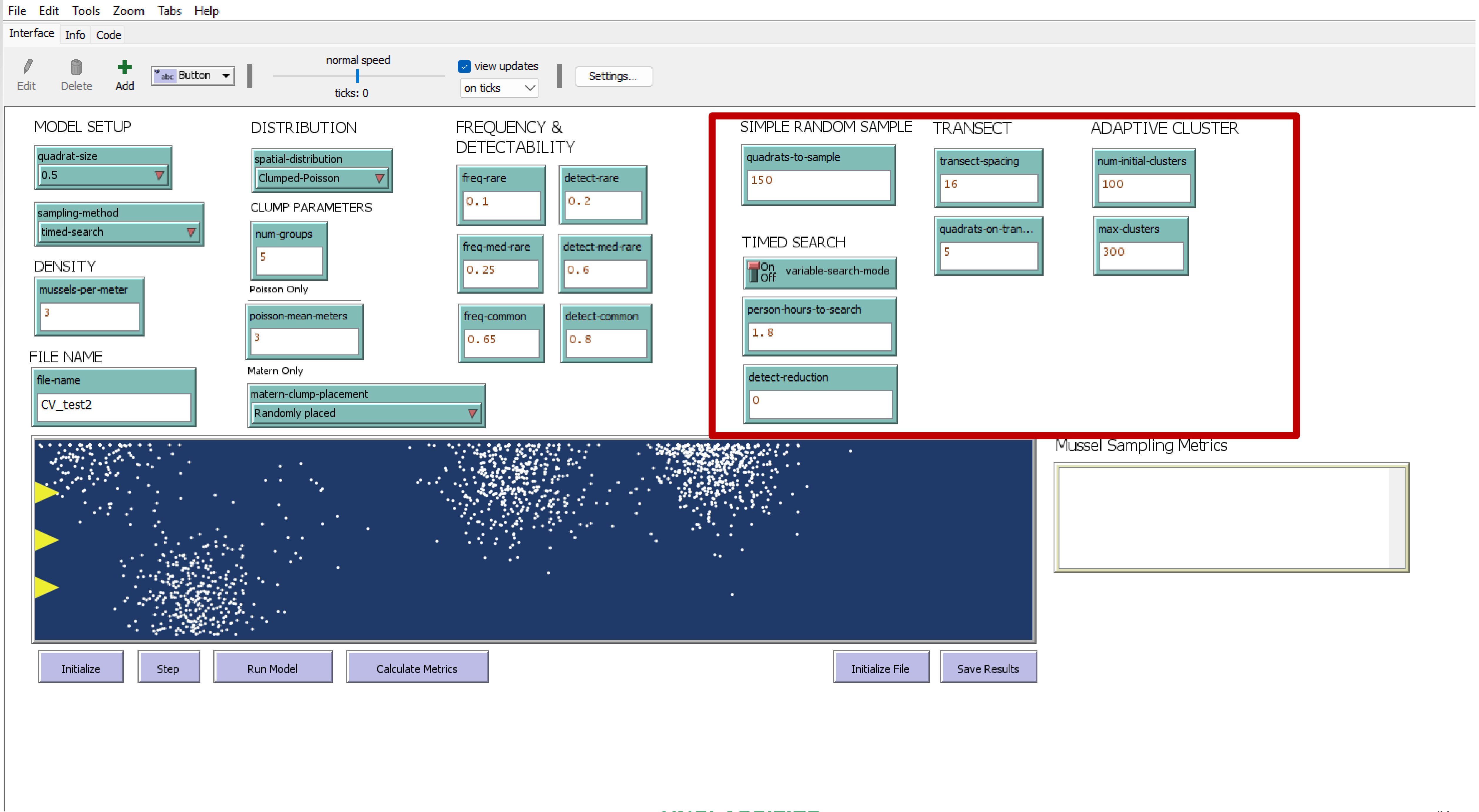
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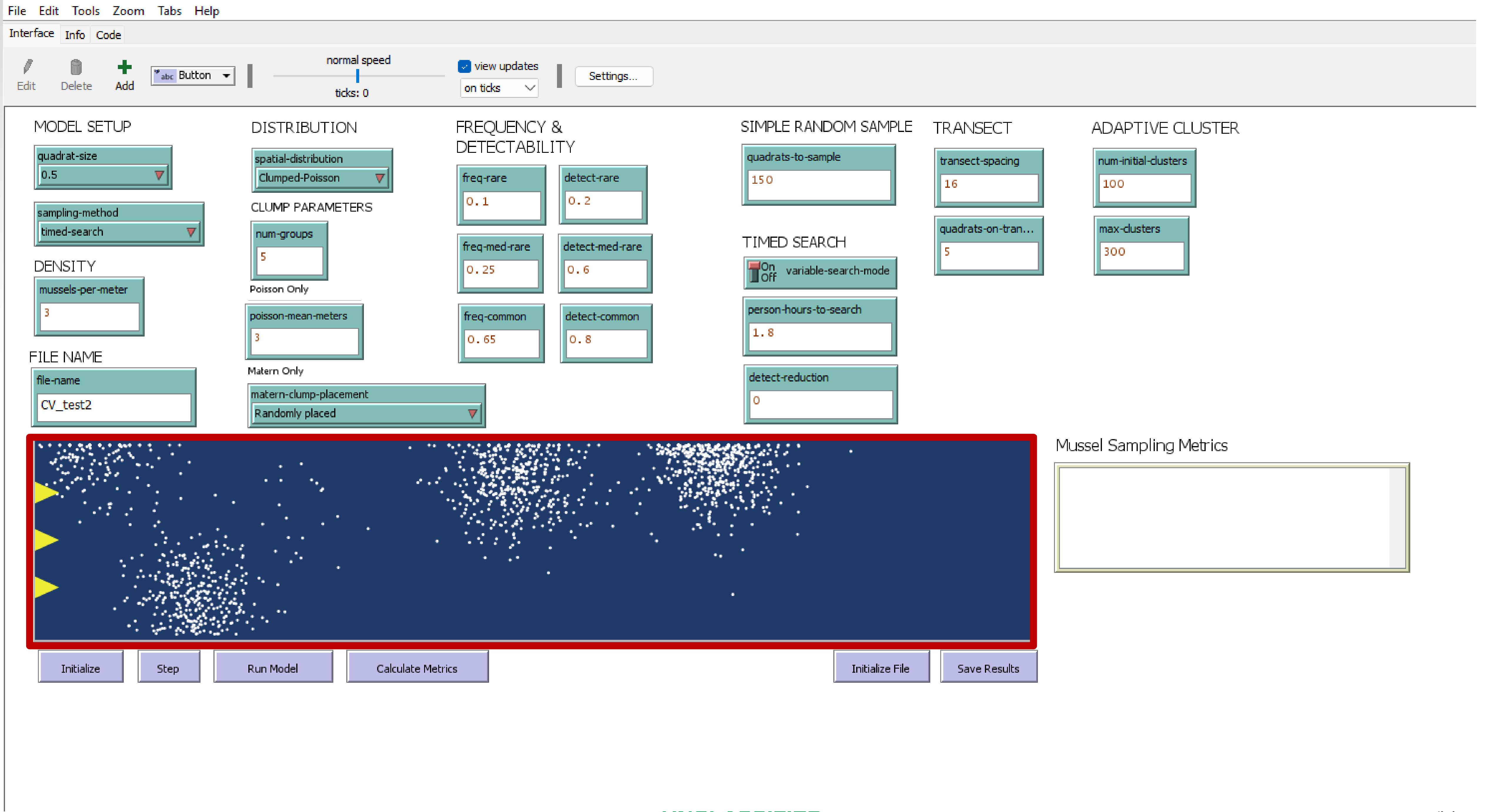
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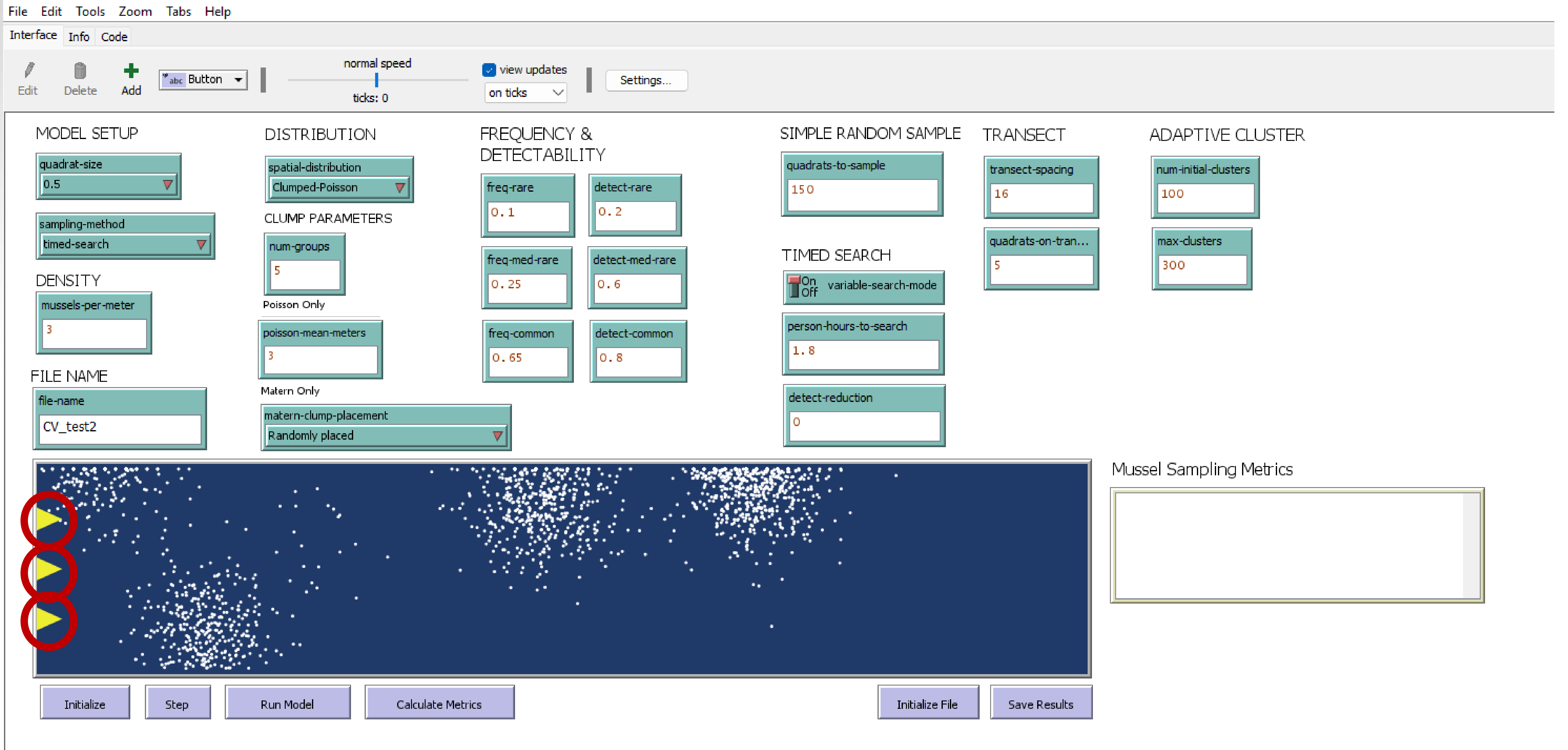
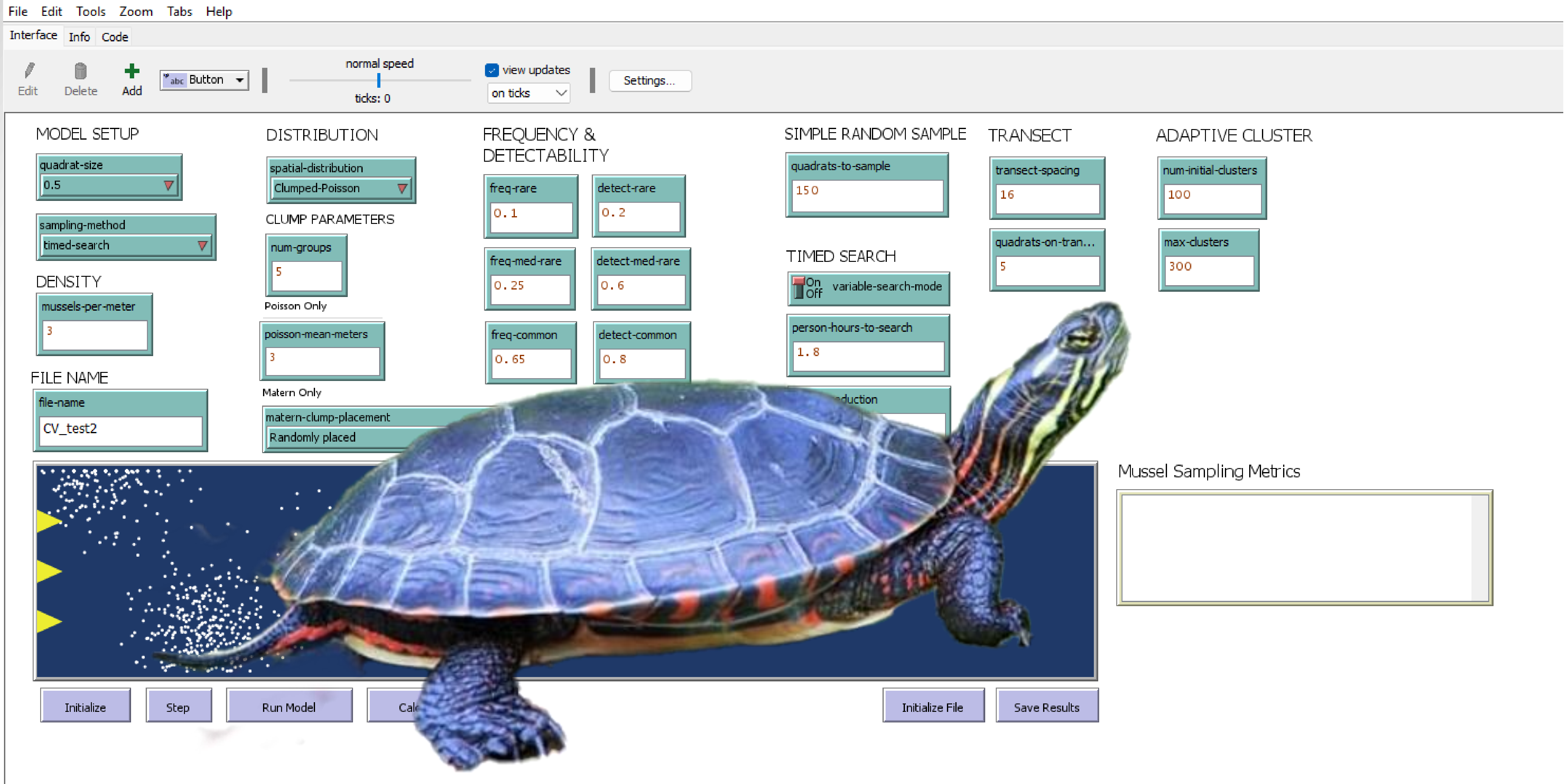


Picture credit: Woolnough Lab, Central Michigan University

Photo credit: Biology.net



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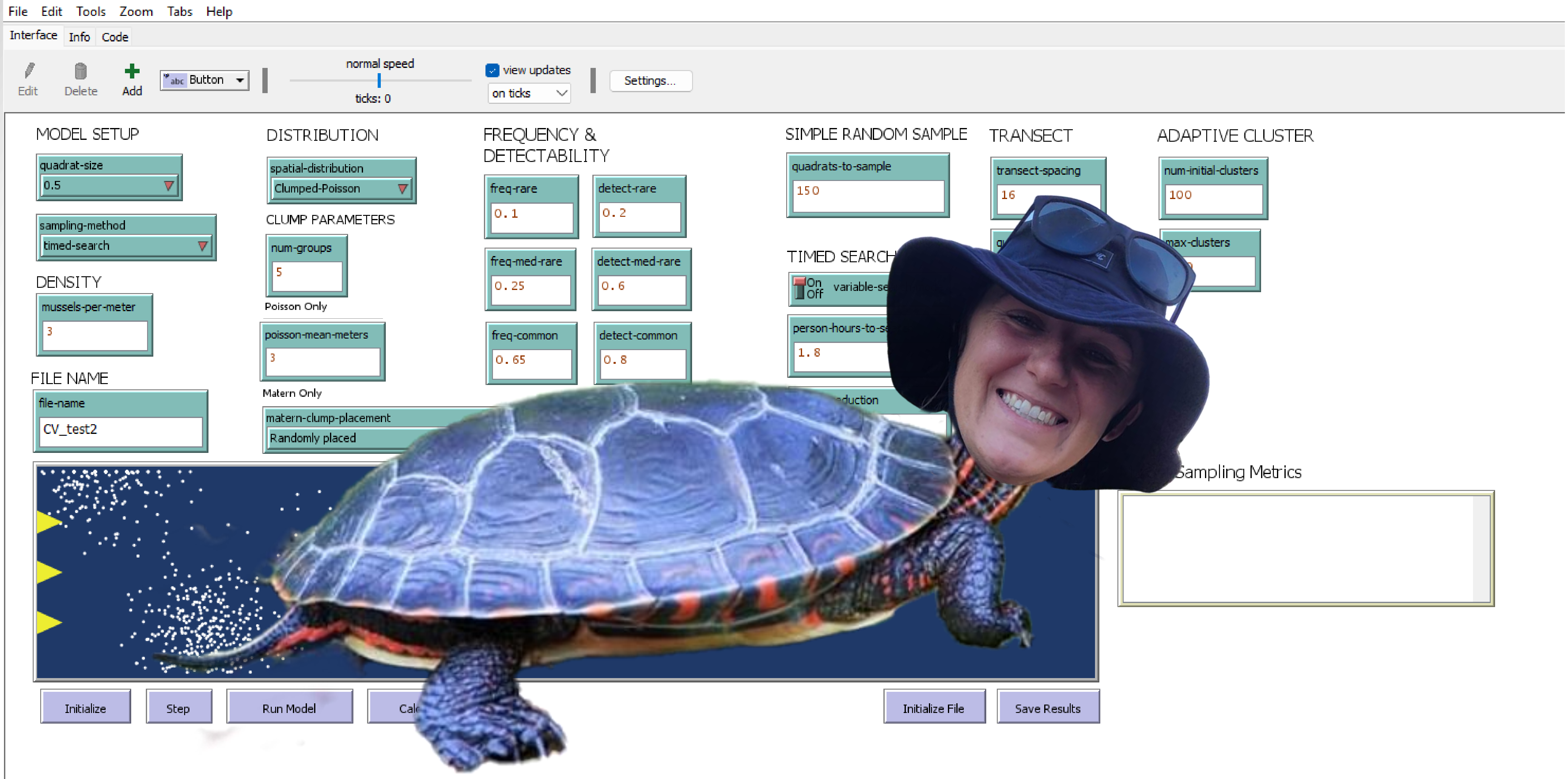

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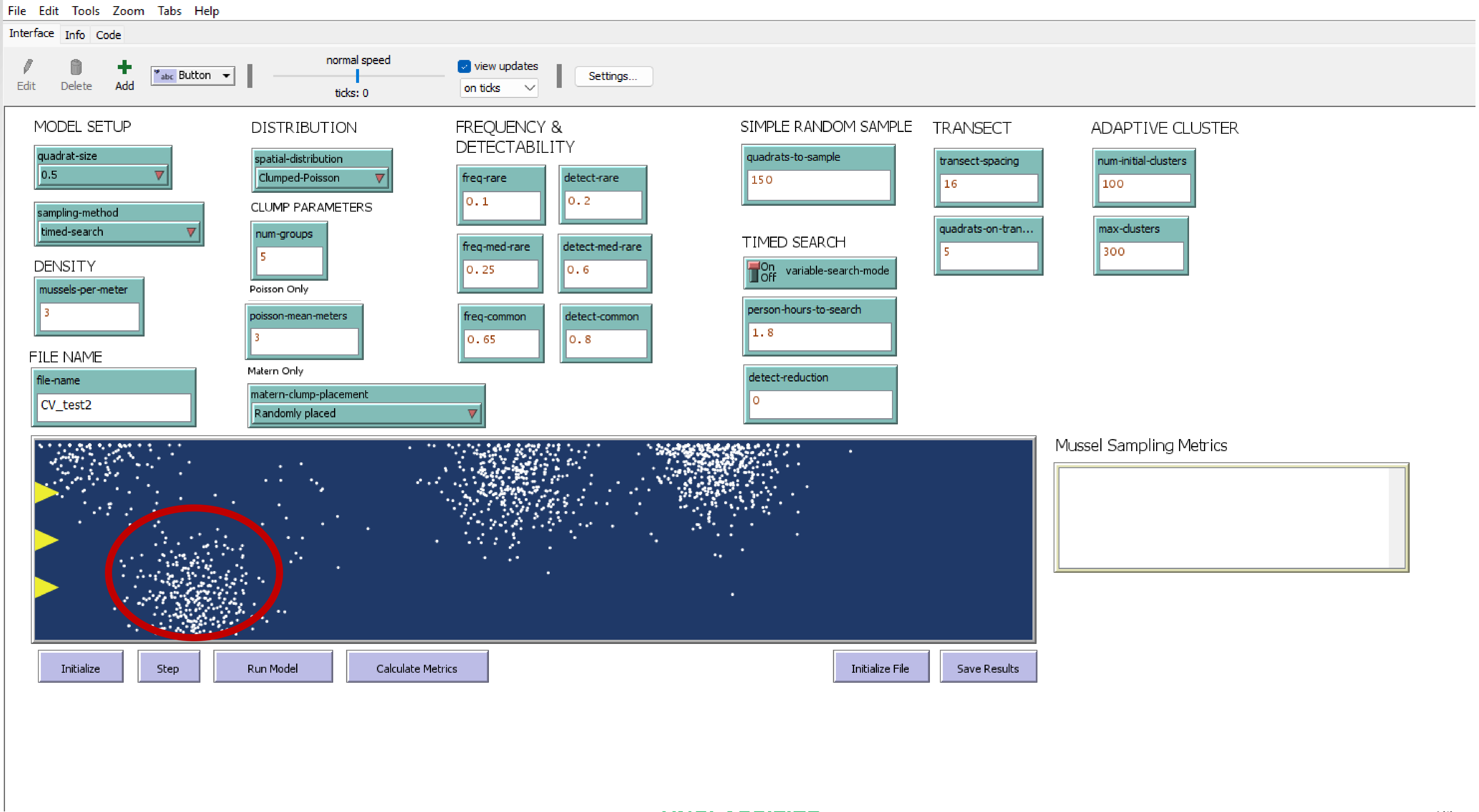
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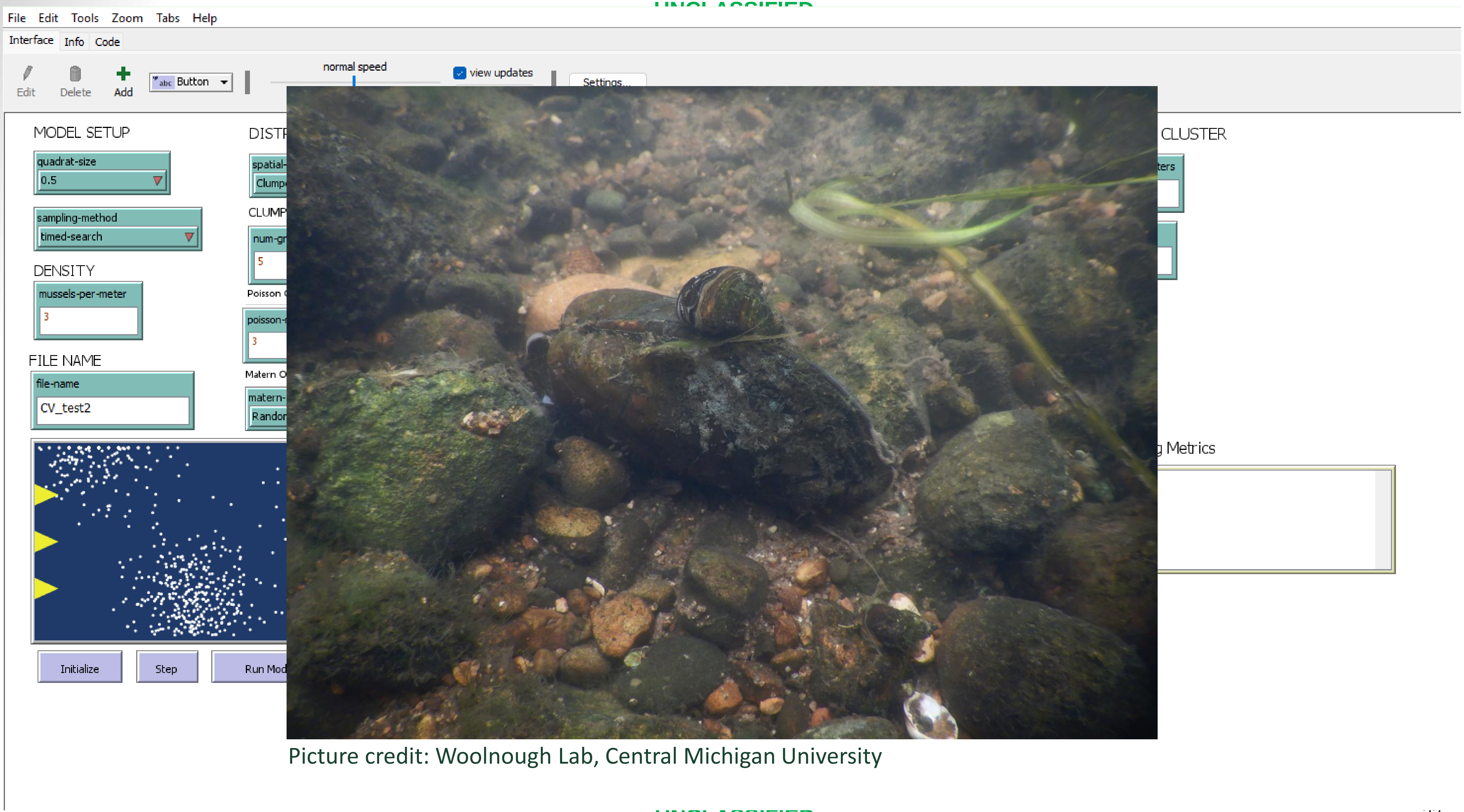

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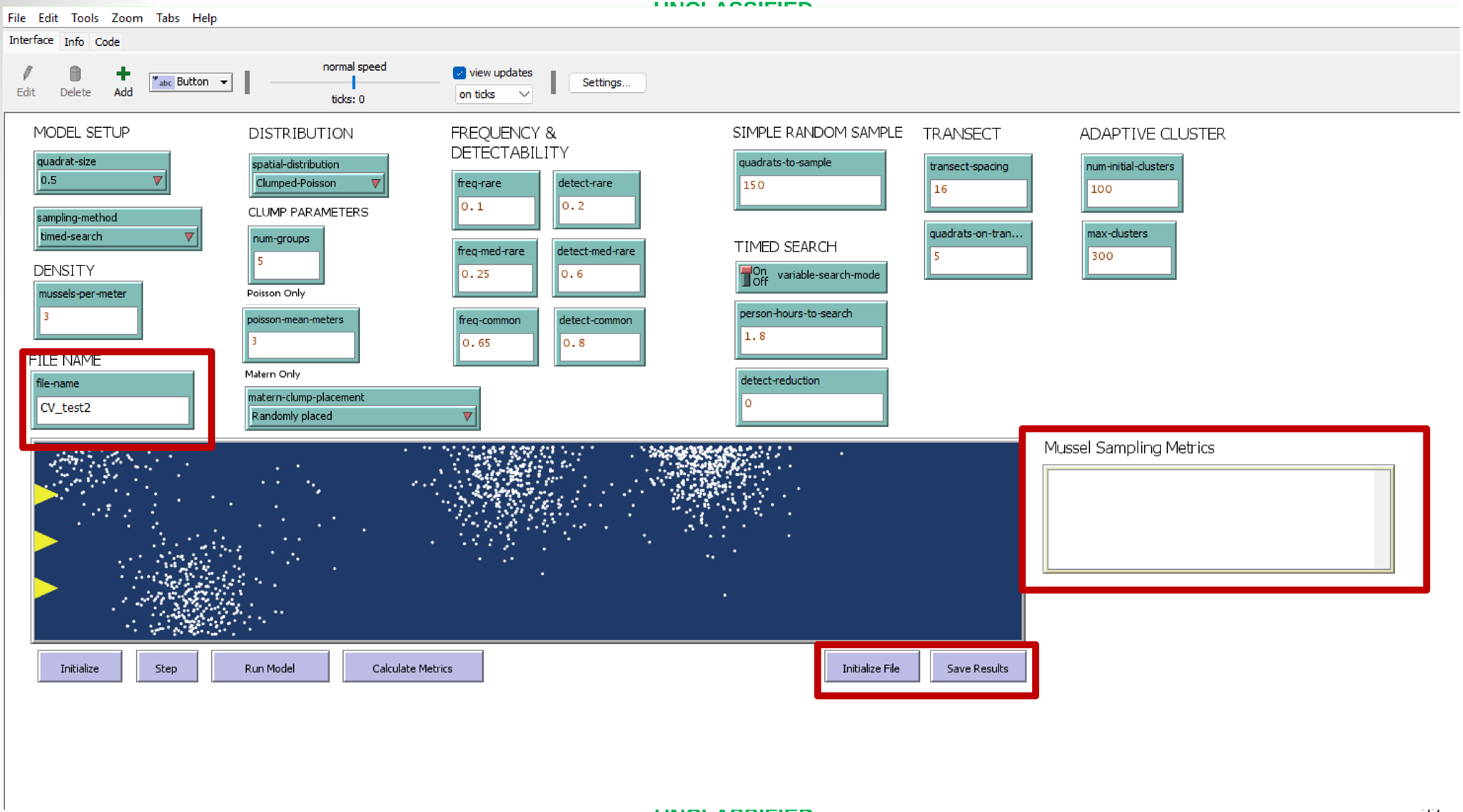

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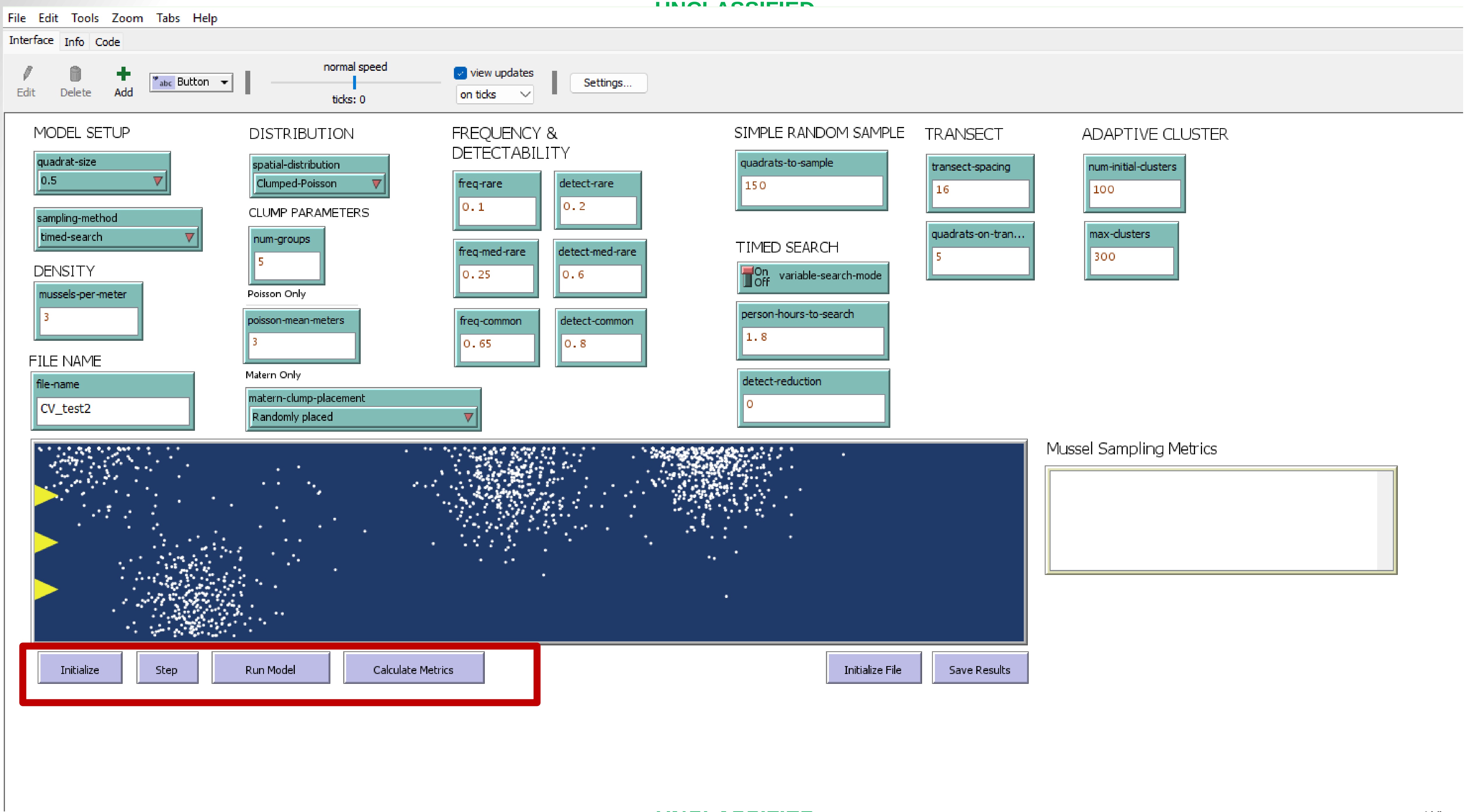
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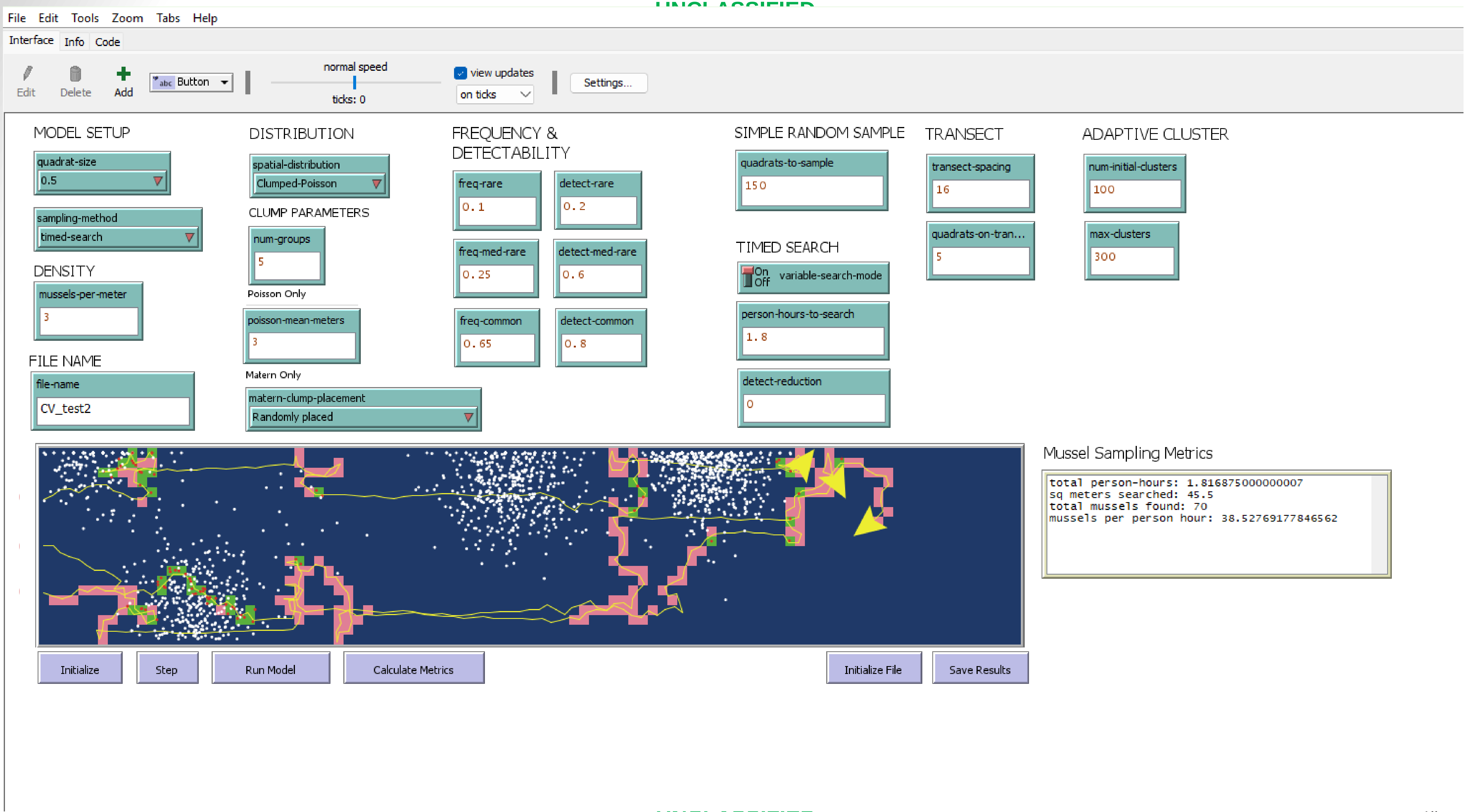

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THE NITTY GRITTY: BREAKING DOWN SAMPL'S CAPABILITIES

Interface Info Code

Find... Check Procedures Indent automatically Code Tab in separate window

```
extensions [GIS matrix table csv];


;variable that has the same value for all the agents in the model across all procedures
globals [
  width-bw-transects  ;width between transects
  transects ;patches in a transect
  #-of-mussels ;total number of mussels in the model
  total-rare-mussels  ;total number of rare mussels in model
  total-med-rare-mussels  ;total number of medium rare mussels in model
  total-common-mussels  ;total number of common mussels in model
  clusters ;patches in an adaptive sampling cluster. If sampled it will be TRUE. else it will be 0
  total-clusters  ;number of patches where in an adaptive sampling cluster. cluster = True
  color-list ;color list for clusters. The color-list is sampled without replacement for clusters, so color-list2 holds the original color list.
  color-list2  ;saved copy of original color-list
  adapt? ;a boolean variable that is TRUE when adaptive sampling should continue.
  maxX maxY ;max x coordinate and max y coordinate
  newPatchSize  ;cell size
  musselSize ;size of mussels dots in UI
  output-file-mussels  ;the filepath where results will be written. Partially defined by file-name input
  total-mussels-sampled  ;the number of mussels that are in patches where quadrat = TRUE. The number of mussels that are sampled
  rare-mussels-sampled  ;same but only counting rare mussels
  common-mussels-sampled  ;same but only counting common mussels
  med-rare-mussels-sampled  ;same but only counting medium rare mussels
  total-mussels-detected  ;number of mussels that are detected
  rare-mussels-detected  ;same but only counting rare mussels
  common-mussels-detected  ;same but with common-mussels
  med-rare-mussels-detected  ;same but with medium rare mussels
  number-of-transects  ;number of transects
  mussel-group-sizes  ;a list that holds all of the mussel group sizes
  poisson-clump-sizes  ;list to store output of clump-size function
  timed-search-minute-counter  ;keeps track or random walk time
  person-hours  ;number of person hours (calc depends on search method)
  mussels-per-surveyor-list  ;a list holding total mussels detected by each surveyor
  total-num-quadrats  ;the number of cells/patches where quadrat = TRUE
  total-quadrats-surveyed  ;the sum of the number of quadrats searched by each surveyor
  estimated-mussel-density  ;number of mussels detected/number of square meters sampled
  sample-cv  ;coefficient of variation for detected mussels
  mussels-per-person-hour  ;number of mussels detected/person hours searched
  hh-estimated-density-m  ;#hh estimation of true population mean
  hh-estimated-total-pop  ;hh estimate of total population
  hh-estimated-density-var  ;hh variance of estimated population mean
  hh-estimated-pop-var  ;hh variance of estimated total population
  var-mean-ratio  ;calculate the variance to mean ratio (using quadrat size)
]


;Attributes that are unique to the class patch
patches-own [
  transect? ;True or False. If the patch is in a transect or not.
  transect-ID ;The ID of the transect that the patch is in. If it's zero, it's not in a transect.
  quadrat? ;True or False. If the patch is sampled
  cluster? ;True or False. Is the patch in a cluster
  cluster-ID ;The ID of the cluster that the patch is in.
  cluster-ring ;What iteration of adaptive sampling is the patch in. If it is in initial random sample it is 0, if it is in the next iteration it is 1. etc.
  cluster-edge? ;if the patch is at the edge of a cluster or not
  parent-patch? ;True or False. If the patch is the center of a poisson cluster
  ellipse-set ;set of patches that compose an ellipse
  ellipse-center? ;True or False. Is the patch the center of an ellipse?
  ellipse? ;Is the patch in an ellipse
  major-axis ;half of the longest length in the ellipse. Formula changes based on custom matern size/locations (ie shore, center, etc)
  minor-axis ;half the shorter length in the ellipse.
  heading-ellipse  ;ellipse orientation (variable is angle)
  network-summary  ;summary of type of mussels that were sampled.
  mussels-on-patch  ;the number of mussels on each patch
]
```

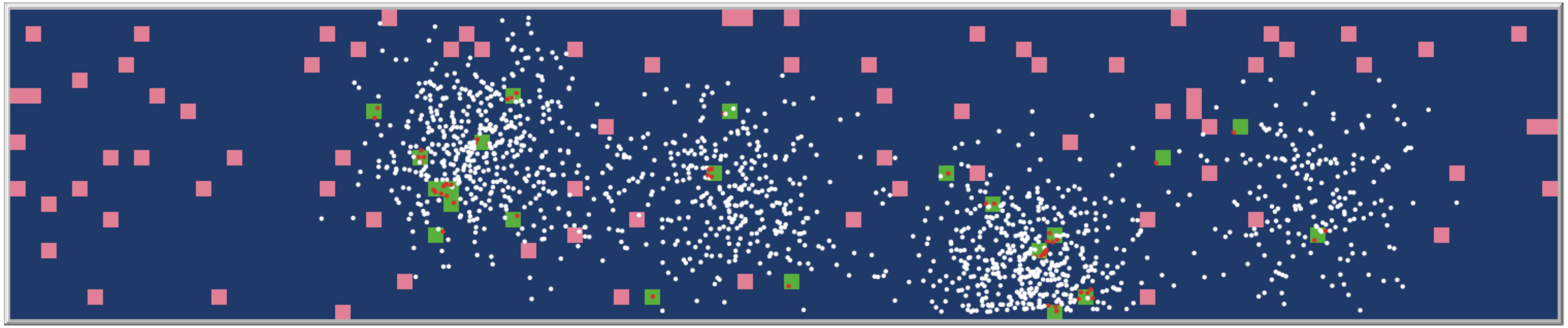
SIMULATING SAMPLING STRATEGIES: SIMPLE RANDOM SAMPLING

Adjustable settings: quadrats-to-sample
Steps to run: initialize
Metric: mussel density (mussels m^{-2})

- Sampled quadrat (empty)
- Sampled quadrat (mussels present and detected)
- Sampled quadrat (mussels present but undetected)
- Unsampled quadrat
- Unsampled mussel

SIMPLE RANDOM SAMPLE

quadrats-to-sample
100



50 m x 10 m area

SIMULATING SAMPLING STRATEGIES: TRANSECT SAMPLING

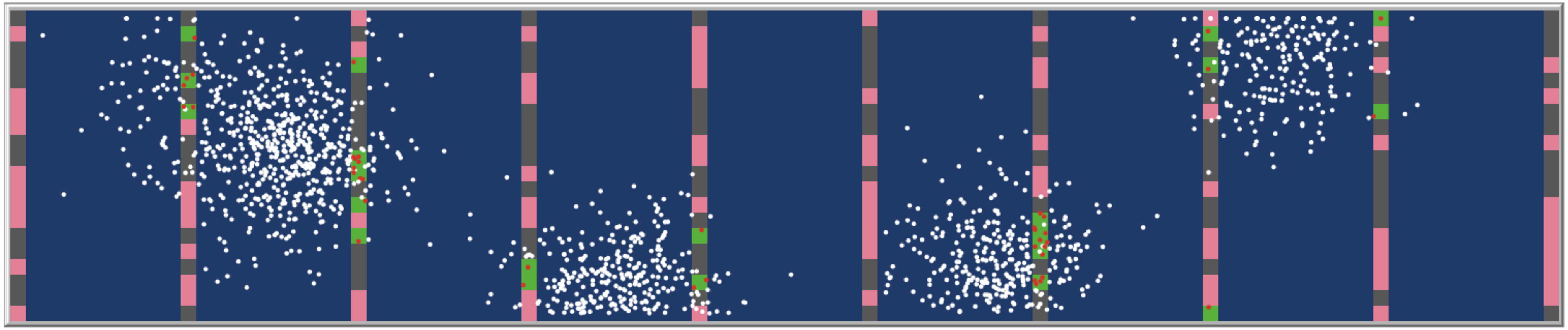
Adjustable settings: transect-spacing; quadrats-on-transect
Steps to run: initialize
Metric: mussel density (mussels m^{-2})

- Sampled quadrat (empty)
- Sampled quadrat (mussels present and detected)
- Sampled quadrat (mussels present but undetected)
- Unsampled quadrat
- Unsampled quadrat on transect
- Unsampled mussel

TRANSECT

transect-spacing
10

quadrats-on-transect
10

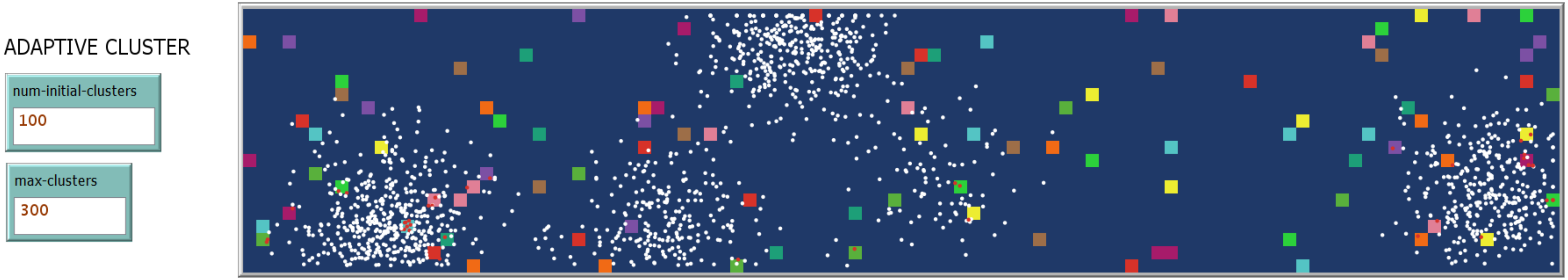


50 m x 10 m area

SIMULATING SAMPLING STRATEGIES: ADAPTIVE CLUSTER SAMPLING

Adjustable settings: num-initial-clusters; max-clusters
Steps to run: initialize; run model
Metric: Hansen-Hurwitz mussel density (mussels m^{-2})

- Adaptive cluster sample
- Unsampled quadrat
- Unsampled mussel

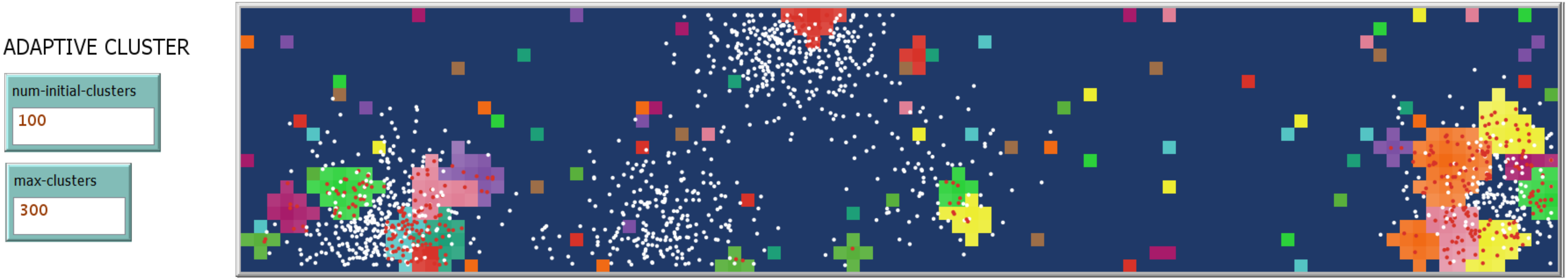


50 m x 10 m area

SIMULATING SAMPLING STRATEGIES: ADAPTIVE CLUSTER SAMPLING

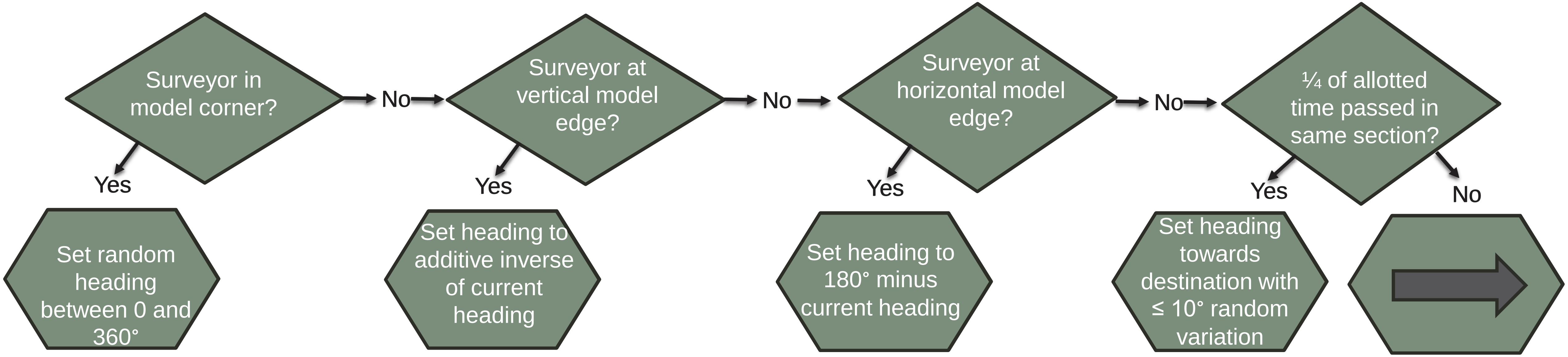
Adjustable settings: num-initial-clusters; max-clusters
Steps to run: initialize; run model
Metric: Hansen-Hurwitz mussel density (mussels m^{-2})

Adaptive cluster sample
Unsampled quadrat
Unsampled mussel

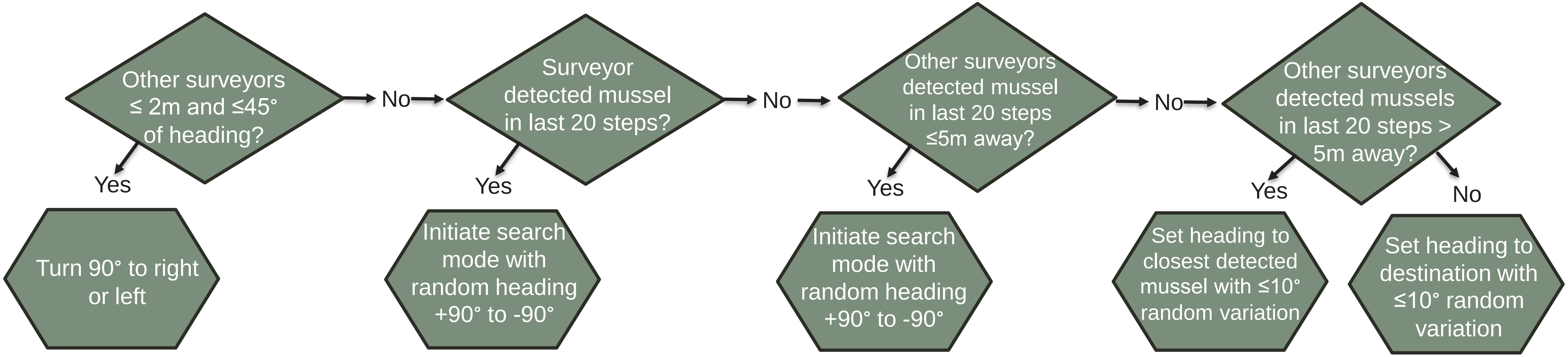


50 m x 10 m area

SIMULATING SAMPLING STRATEGIES: QUALITATIVE TIMED SEARCHES



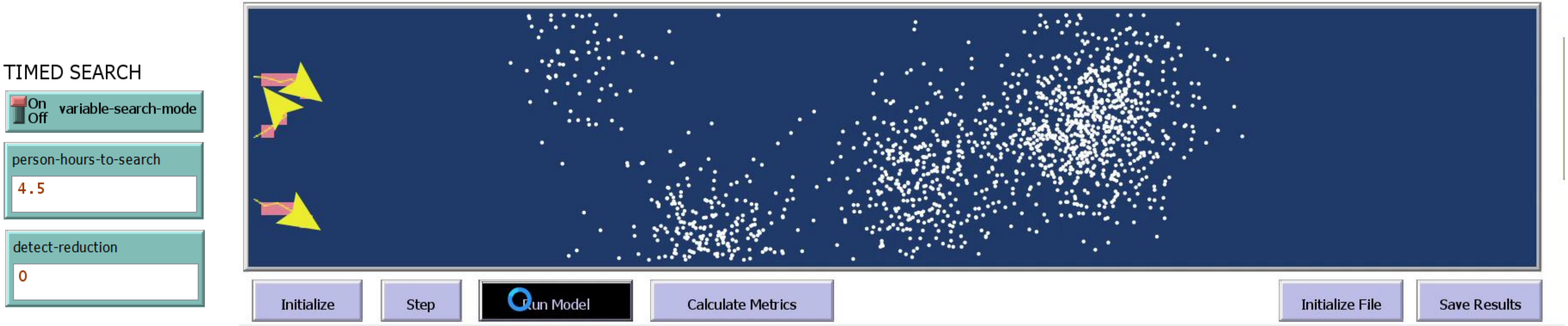
SIMULATING SAMPLING STRATEGIES: QUALITATIVE TIMED SEARCHES



SIMULATING SAMPLING STRATEGIES: QUALITATIVE TIMED SEARCHES

Adjustable settings: variable-search-mode; person-hours-to-search, detect-reduction
Steps to run: initialize; run model
Metric: catch-per-unit-effort (mussels p-h^{-1})
Search rate: 0.5 m min^{-1}

- Sampled quadrat (empty)
- Sampled quadrat (mussels present and detected)
- Sampled quadrat (mussels present but undetected)
- Unsampled quadrat
- Unsampled mussel



50 m x 10 m area

SAMPL'S ASSUMPTIONS

SAMPL assumes that:

- Detectability is perfect for quantitative methods and does not vary from simulation to simulation
- Surveyors have equal skill and search experience
- Surveyors perceive a homogenous habitat

Human behavior is incredibly complex!

Photo credit: Tonya Ramey

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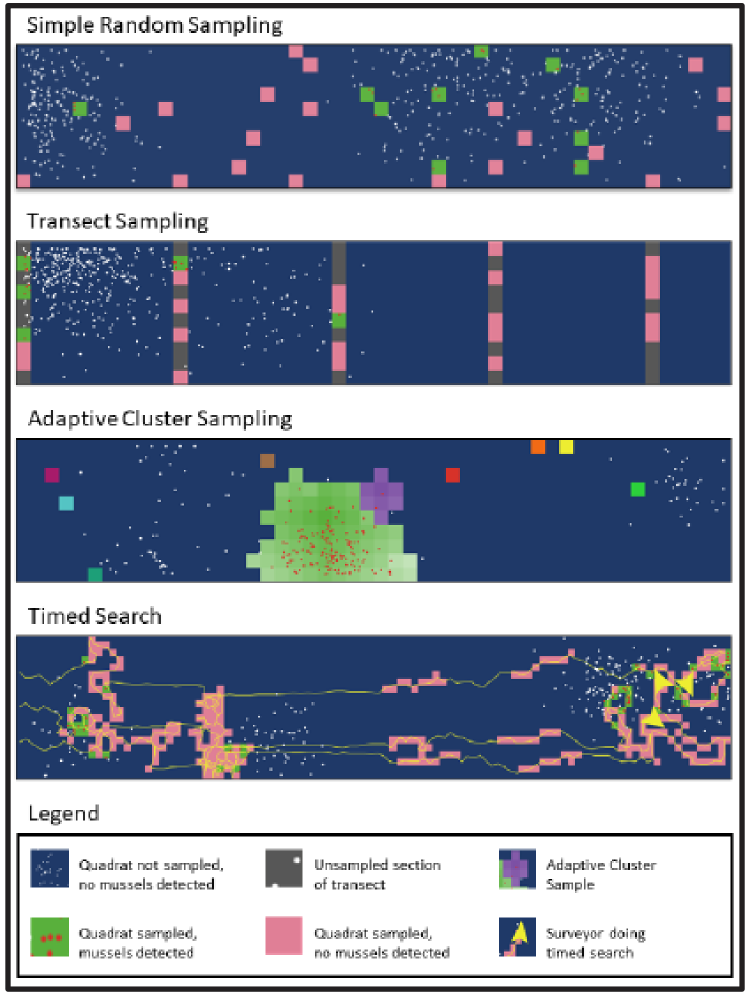
TAILORING SAMPL's CAPABILITIES TO YOUR NEEDS

Using the graphical user interface (GUI), users can adjust:

- Quadrat size
- Sampling method
- Organism density
- Spatial distribution
- Species' frequency and detectability
- Sampling schemes

BUT: if you're thinking, that's not how our team samples...



Credit: Iris Foxfoot

TAILORING SAMPL's CAPABILITIES TO YOUR NEEDS

For more advanced control of SAMPL's procedures, users can glance under the hood and adjust the code:

- Adjust number of surveyors
- Adjust surveyor behavior and decision rules
- Adjust default spatial distributions
- Adjust number of species
- Adjust population metrics

```
;procedure to move surveyors
to timed-search

  ;determine if search mode is T or F
  ask surveyors[
    ifelse variable-search-mode = True [
      ( ifelse
        tick-since-last-find <= 20 [
          set search-mode True]
        ticks mod 10 = 0 [
          set search-mode search-mode = False]
        [])
    ]
    [set search-mode True]
  ]

  ;check if surveyors reached destination
  ask surveyors [
    if pxcor = destination [
      set reached-destination-once? true
      set reached-destination? True
    ]
  ]

  ;check if surveyors are out of time
  ask surveyors [

    set out-of-time? False

    set quarter find-quarter
```

Snippet from SAMPL code

HOW CAN YOU APPLY SAMPL?

Examples of potential SAMPL applications:

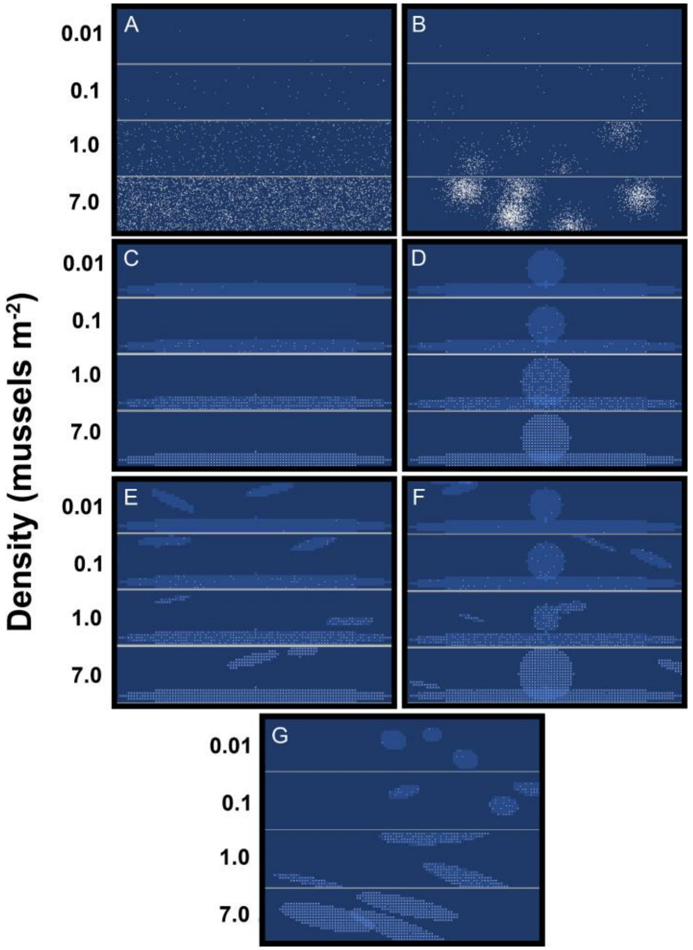
- Exploratory assessments
- Survey planning
  - Estimating sampling effort
  - Comparing performance of different sampling methods
  - Assessing how population characteristics impact survey efficacy

Photo credit: Kiara Cushway

SAMPL IN ACTION: EVALUATING THE EFFECTS OF DENSITY, SPATIAL DISTRIBUTION, AND SAMPLING METHOD ON POPULATION ESTIMATES

We tested:

1) How do mussel density and spatial distribution affect catch-per-unit-effort (CPUE; defined in this case as mussels detected per person-hour) during qualitative timed searches?



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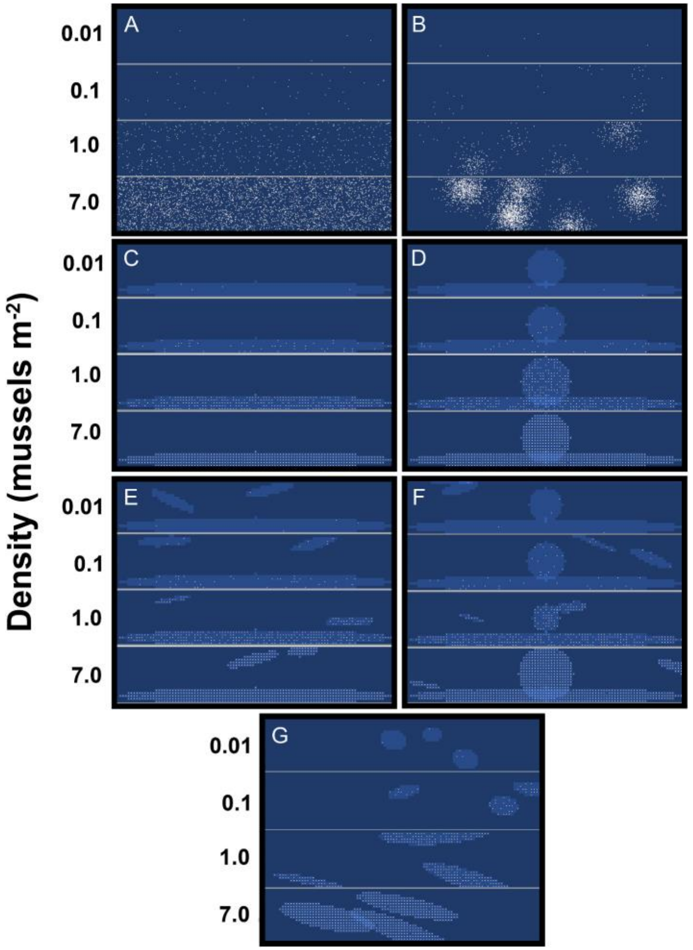
SAMPL IN ACTION: EVALUATING THE EFFECTS OF DENSITY, SPATIAL DISTRIBUTION, AND SAMPLING METHOD ON POPULATION ESTIMATES

We tested:

2) What effects do spatial distribution, density, and sampling method have on the probability of mussel detection and the accuracy and precision of density (or CPUE) estimates during quantitative and qualitative surveys?



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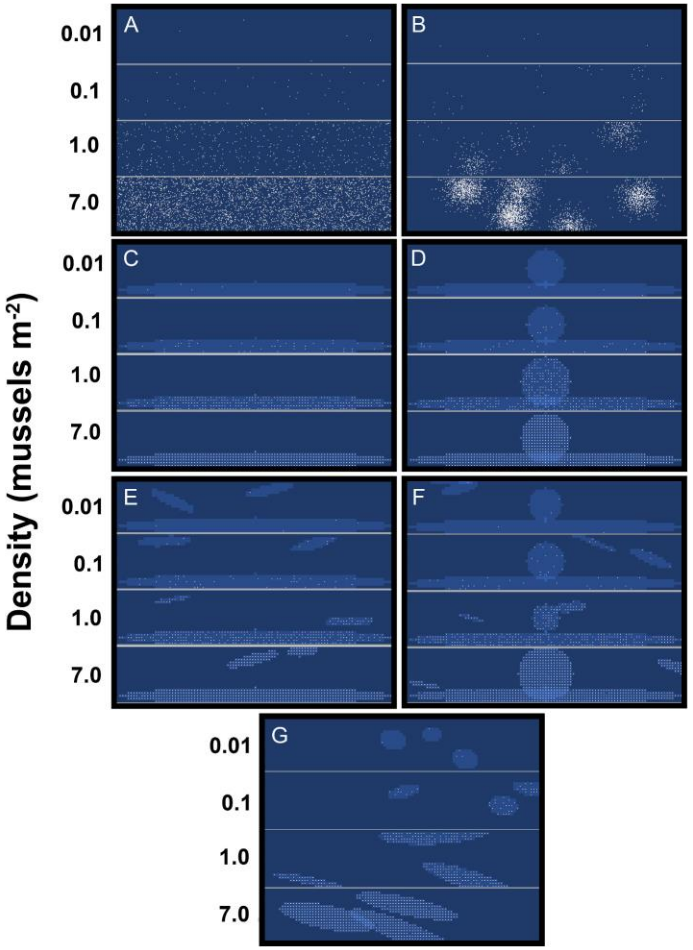
SAMPL IN ACTION: EVALUATING THE EFFECTS OF DENSITY, SPATIAL DISTRIBUTION, AND SAMPLING METHOD ON POPULATION ESTIMATES

We tested:

3) How does sampling effort affect the accuracy of density estimates and the proportion of the total population that is sampled?



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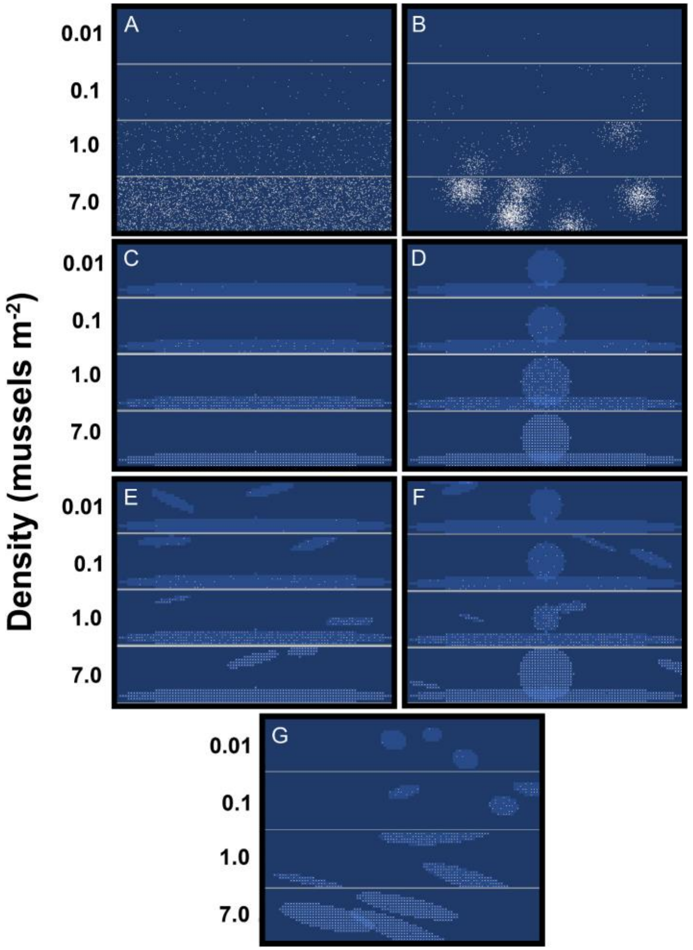
SAMPL IN ACTION: EVALUATING THE EFFECTS OF DENSITY, SPATIAL DISTRIBUTION, AND SAMPLING METHOD ON POPULATION ESTIMATES

Model settings:
- Density: 0.01, 0.1, 1.0, 7.0 mussels m^{-2}
- Spatial distribution: random, clumped Poisson, clumped Matern
- Detectability: 100% for all quantitative methods; 30% for qualitative timed searches



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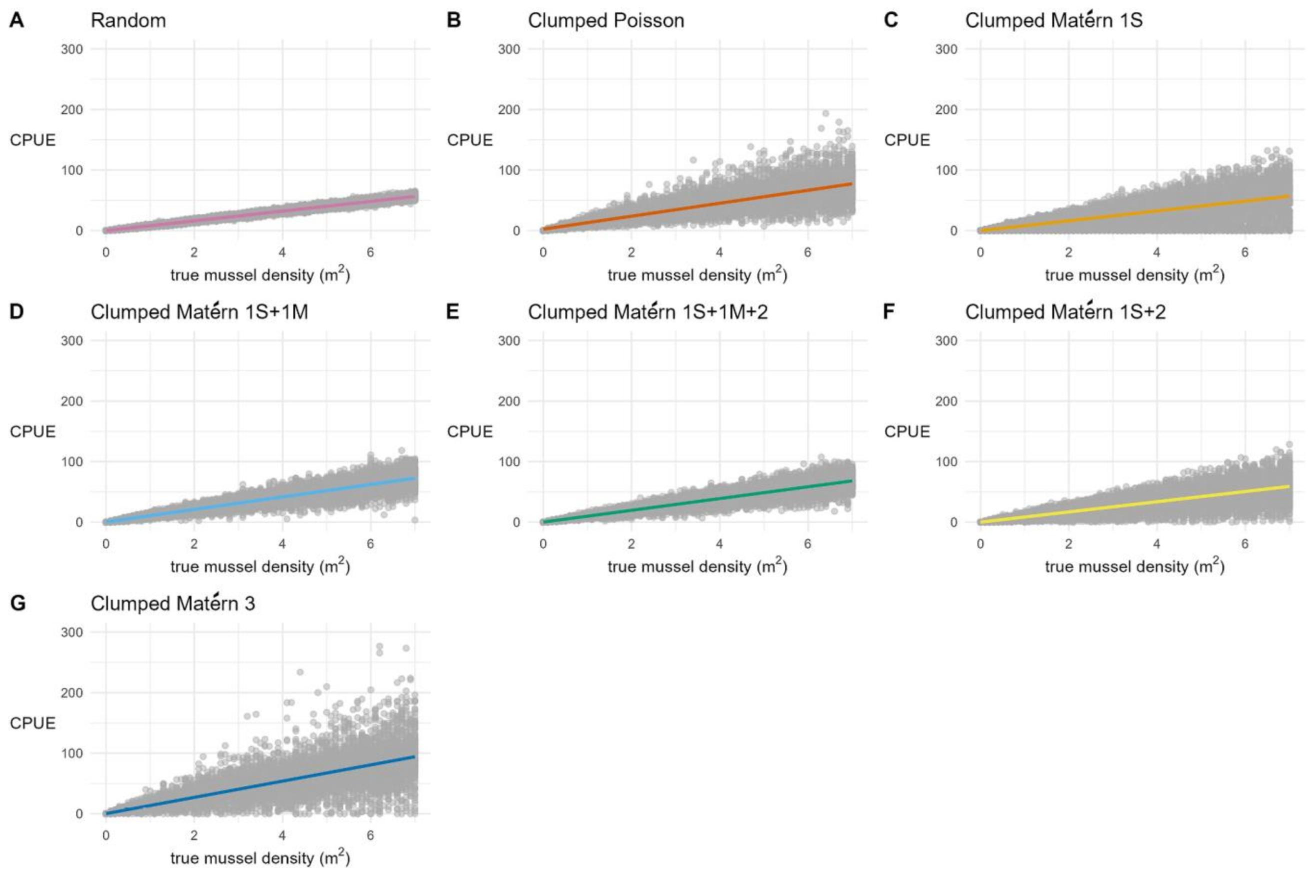
EFFECTS OF DENSITY AND SPATIAL DISTRIBUTION ON CPUE ESTIMATES

- True mussel density and CPUE have a strong positive relationship (R^2 ~0.94-0.99)

- HOWEVER: When mussels are spatially clustered, there may be high variation in CPUE estimates, particularly as true mussel density increases



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EFFECTS OF DENSITY, SPATIAL DISTRIBUTION, AND SAMPLING METHOD ON POPULATION ESTIMATES

We tested the performance of sampling methods for each density and spatial distribution combination based on:

- Accuracy (measured as percent error)
- Detection (measured as pseudoabsence rate and proportion of total population detected)
- Precision (measured as coefficient of variation)

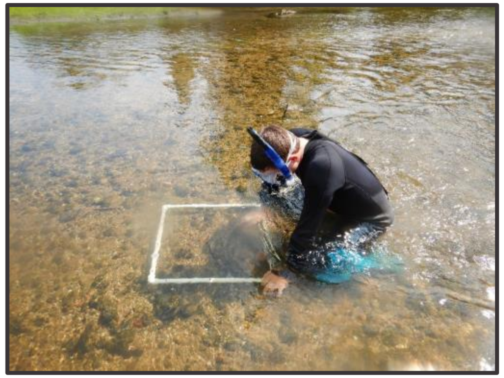

Photo credit: Woolnough Lab, Central Michigan University

Photo credit: Woolnough Lab, Central Michigan University

Photo credit: Schwalb Lab, Texas State University

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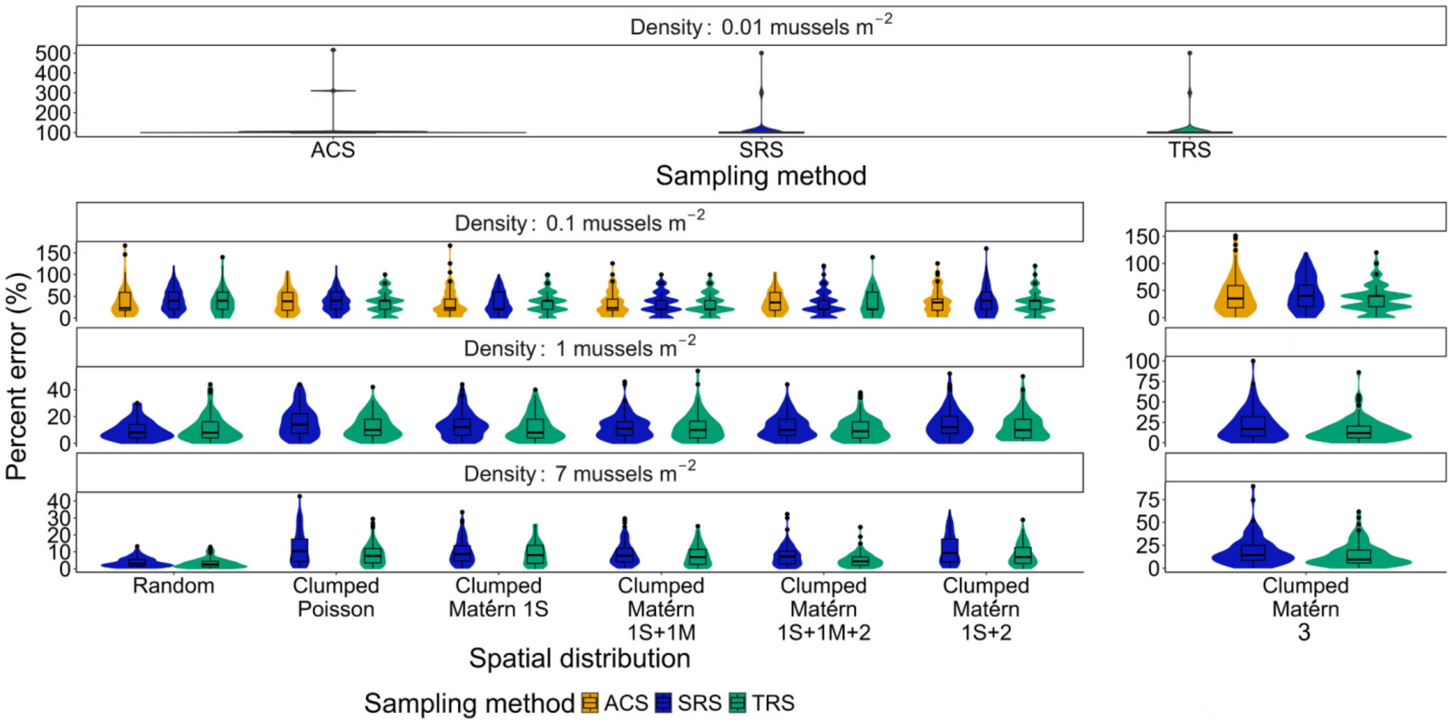
EFFECTS OF DENSITY, SPATIAL DISTRIBUTION, AND SAMPLING METHOD ON POPULATION ESTIMATES

- All sampling methods performed relatively poorly when mussels were rare (*i.e.*, 0.01 mussels m^{-2})

- Transect searches often performed the best in terms of accuracy and precision

- When search area and time were approximately constant, qualitative timed searches performed worse than quantitative methods



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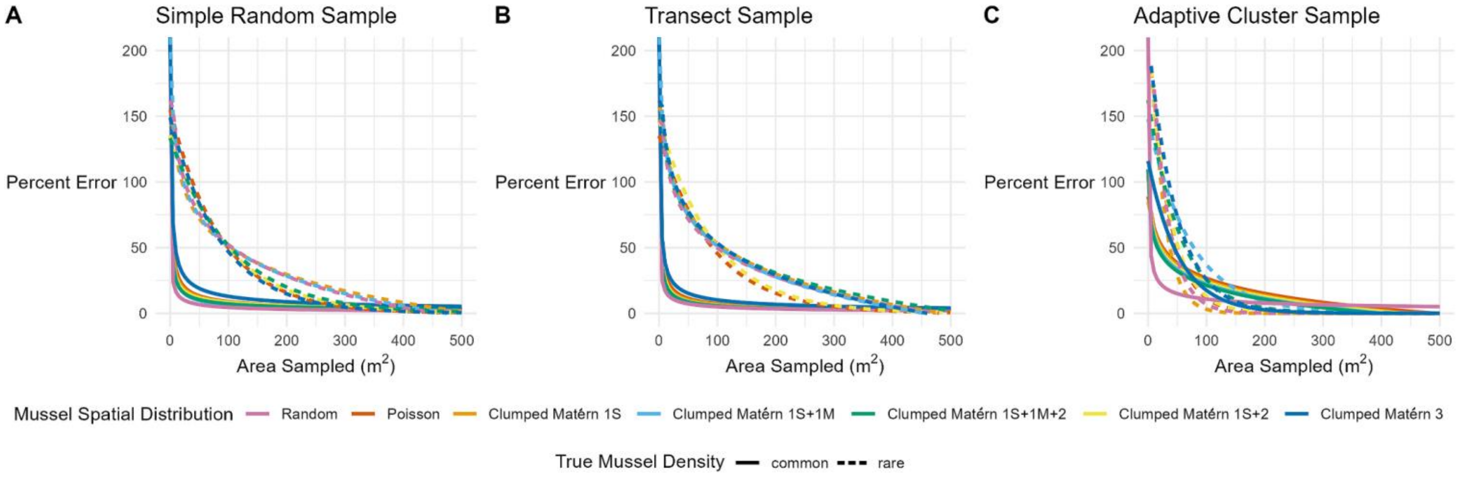
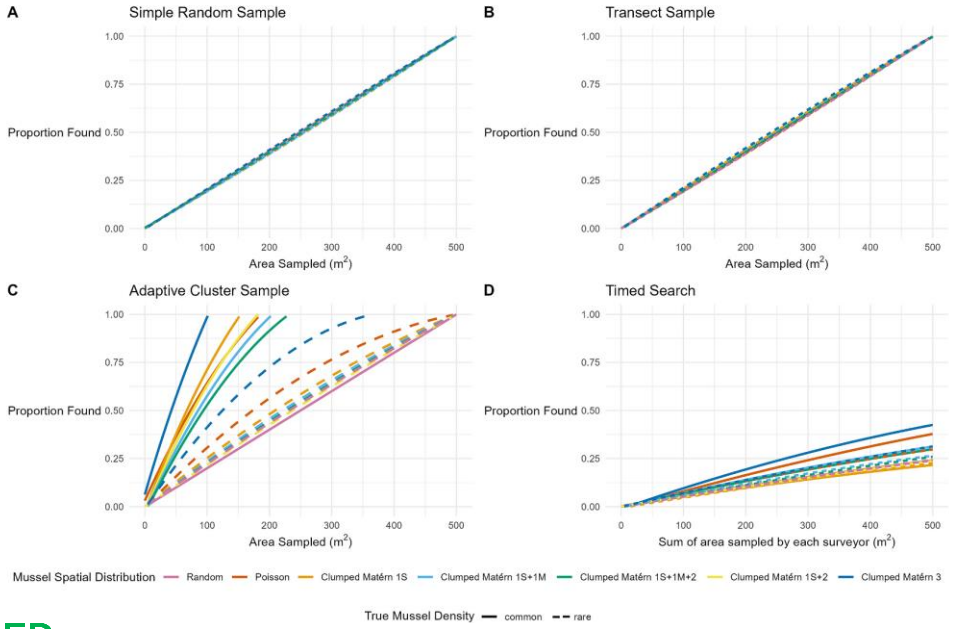
EFFECTS OF SAMPLING EFFORT ON ACCURACY AND DETECTION

- The level of effort needed to achieve acceptable accuracy tends to increase as density decreases

- Populations that are spatially clustered may often require higher sampling effort compared to randomly distributed populations

- Determining search effort *a priori* may help promote effective survey designs





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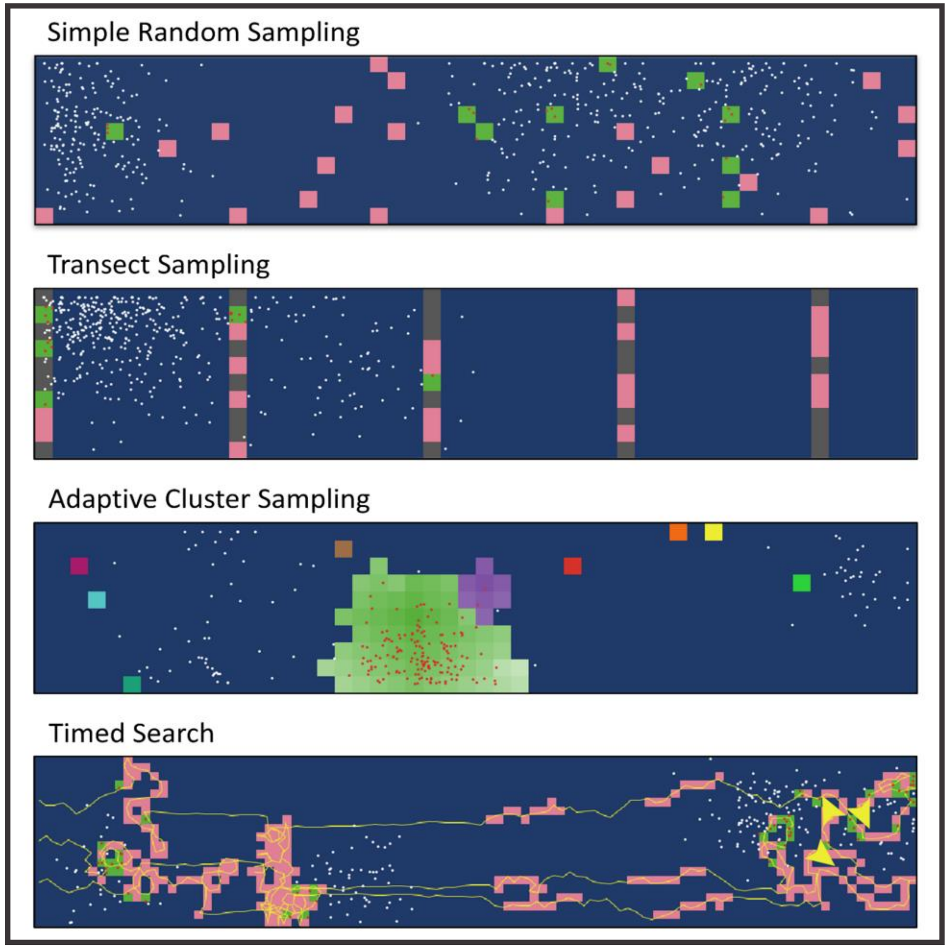
CONCLUSIONS

- Agent-based modeling allows us to capture dynamics of sampling strategies that are difficult to evaluate in field settings

- SAMPL can help researchers improve field sampling practices by critically evaluating how certain methodological decisions affect survey outcomes

- Practically, models like SAMPL can help practitioners improve the performance of field surveys, and ultimately, management and conservation actions, by providing insight into the reliability of various sampling methods



Credit: Iris Foxfoot

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Questions or comments?

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Acknowledgements

- ANSRP focus on Next Generation Ecological Modeling
- Dr. Safra Altman
- Dr. Amy Yarnall
- David Swearingen

Thank you!

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