## Lionfish Matrix Population Model

A matrix population model for lionfish was developed by Morris et al. (2011) to investigate potential approaches for controlling the invasive species. Lionfish start reproducing one year after birth. Once they mature, they are very fecund, releasing a large number of eggs each month. These life history strategies make them very successful invasive species. Morris et al. (2011) took parameters from other studies (Table S1) and produced a three-stage (larvae, juvenile, and adult) population matrix (Table S2):

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The time step of the model is one month, and we refer to this model as L1.

Table S1. Parameter values for lionfish in Morris et al. (2011). These values are used for our calculations.

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| --- | --- | --- |
| **Parameters** | **Value** | **Units** |
| **Larval mortality (*ML*)** | 0.350 | days-1 |
| **Adult mortality (*MA*)** | 0.052 | months-1 |
| **Juvenile mortality (*MJ*)** | 0.165 | months-1 |
| **Proportion female (*ρ*)** | 46% |  |
| **Larval duration (*DL*)** | 30 | days |
| **Egg mortality (*ME*)** | 0.310 | days-1 |
| **Fecundity (*f*)** | 194,577 | Eggs months-1 female-1 |
| **Egg duration (*DE*)** | 3 | days |

The model has two major problems. First, the model is a post-breeding census model so that the survival of adults needs to be incorporated into the fertility term *RA*. Because the fertility term included 3-day survival of eggs, we modified the fertility rate by multiplying it by the 27-day survival rate of adults. This assumes one month consists of 30 days. Second, lionfish start reproducing in one year (i.e. 12 months). If so, they should spend 11 months on average in the juvenile stage rather than 12 months because individuals spend one month in the larvae stage. Therefore, the coefficients in *PJ* and *GJ* were modified to 10/11 and 1/11, respectively. These corrections were incorporated into the second model (L2; Table S2).

According to the model, individuals spend one month in the larvae stage and 11 months on average in the juvenile stage. Then, they mature and reproduce. Therefore, the first offspring appears in 13 months on average. One way to correct for the problem is to assume that individuals in pre-mature stage (juvenile stage) reproduce at the same time they mature when a post-breeding census model is used (e.g. Brault and Caswell 1993). This adds a fertility rate to the pre-mature stage. In model L2,  of juveniles mature each month. Therefore, in the next model, fertility rate  was added for the juvenile stage (i.e. <1,2> element of the matrix. In words, this means that  of juveniles mature and survives over 27 days, proportion  of them are females, which produce  eggs, and then, those eggs survive over  days. We refer this model as L3.

The transition rate calculations in the above three models (L1-L3) assume proportion makes a transition from juvenile to adult stage when the average duration is . This is an approximation assuming the survival rate is 1. However, in reality, some of them die before reaching the final age within the stage so that the proportion making the transition should be less. To account for the deaths, Crouse et al. (1987) developed a formula incorporating the survival rate. For the lionfish model, the transition rates for juvenile stage *J* become

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where  is the proportion of juveniles that survive and remain in the juvenile stage,  is the proportion of juveniles that survive and transition into the adult stage, and  is the stage specific survival rate of juveniles. The associated fertility rate for the juvenile stage is

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We refer to this model as L4.

The above transition calculation is accurate when λ is close to 1. When it is far from 1, *PJ* and *GJ* calculations need to be modified incorporating λ (Crowder et al. 1994). For the juvenile stage of lionfish,

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In this method, λ is needed to calculate a population matrix, but λ is a quantity calculated from a population matrix. However, Crowder et al. (1994) have demonstrated that λ can be obtained iteratively. In this approach, λ is initially set to an arbitrary value, the population matrix with the initial λ is used to calculate a new λ, and then the population matrix is modified using the updated λ. We refer to this model as L5.

Finally, the Leslie matrix was constructed based on the parameters in the table (M6). This model consists of 13 age classes with fertility rates on 12th and 13th age classes. In this model, age class 1 has the survival rate of , age classes 2 to 12 have the survival rate of , and age class 13 has survival rate of , which appears in the <13,13> element of the matrix. Fertility rates of 12th and 13th age classes are given by  and  , respectively.

Table S. Elements of three-stage population matrices for lionfish under L1-L5. Values are rounded values. To obtain exact values used in calculations, insert the parameter values in Table S1 into the notations shown in this table. Note  .

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Value | Notation | Value | Notation | Value | Notation |
| **Model** | **L1** | | **L2** | | L3 | |
| ***GL*** | 3x10-5 |  | 3x10-5 |  | 3x10-5 |  |
| ***PJ*** | 0.777 |  | 0.771 |  | 0.771 |  |
| ***GJ*** | 0.071 |  | 0.077 |  | 0.077 |  |
| ***PA*** | 0.949 |  | 0.949 |  | 0.949 |  |
| ***RJ*** | 0 | -- | 0 | -- | 2767 |  |
| ***RA*** | 35315 |  | 33799 |  | 33700 |  |
|  | **L4** | | **L5** | |  |  |
| ***GL*** | 3x10-5 |  | 3x10-5 |  |  |  |
| ***PJ*** | 0.818 |  | 0.826 |  |  |  |
| ***GJ*** | 0.030 |  | 0.022 |  |  |  |
| ***PA*** | 0.949 |  | 0.949 |  |  |  |
| ***RJ*** | 1062 |  | 783 |  |  |  |
| ***RA*** | 33700 |  | 33700 |  |  |  |

Using the six population matrices, asymptotic population growth rate λ (Figure S1), stable stage distribution (Figure S2), reproductive value (Figure S3), the sensitivity (Figure S4) and elasticity (Figure S5) of the population growth rate to stage specific survival rate and fecundity (*f*), damping ratio (Figure S6), and generation time (Figure S7) were calculated. To obtain λ under L5 using the iterative method, initial λ was set to 1. Reproductive values for all models were scaled so that the reproductive value of the larval stage is 1. For calculating the stable stage distribution and sensitivity under L6 for the juvenile stage, corresponding values for age-classes 2 to 12 were summed. For reproductive value for juvenile stage under L6, the weighted mean of reproductive values for age classes 2 to 12, where the weight is given by their stable stage distribution, was calculated. For calculating the sensitivity of lambda under L4 and L5, numerical differentiation was used because juvenile survival appears in multiple elements of the matrix under both models, and λ appears in multiple elements under L5. In this study, generation time was defined as the mean age of mothers and calculated using the formula in Bienvenu and Legendre (2015).



Figure S. Asymptotic population growth rates λ of a population under models L1-L6.



Figure S. Stable stage distribution of juvenile stage and adult stage of models L1-L6.

Figure S. Reproductive value of juveniles and adults of a population under models L1-L6.



Figure S. Sensitivity of asymptotic population growth rate to survival and fertility rates of a population under models L1-L6.



Figure S Elasticity of lambda to survival and reproduction of a population under models L1-L6.

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Figure S. Damping ratio of a population under models L1-L6.



Figure S. Generation time of a population under models L1-L6.

## Alligator Matrix Population Model

Stage-structured population matrices were constructed for two alligator populations by Duhman et al. (2014) to compare the status of northern and southern populations. Dunham et al. (2014) took parameters from other studies (Table S3), and constructed a model consisting of five stages for each population. Because they did not have population specific estimates of survival rates, they used the same rates for both populations.

Table S. Parameter values for northern and southern populations of Alligator. Table was taken from Dunham et al. (2014). These values are used for our calculations.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Stage: *i*** | **Size (cm)** | **Stage Duration** *Di***(years)** | **Survival Rate** | **Fecundity *f* (number x year-1)** |
| **Northern Population** | | | | |
| **Egg: E** | 0 | 0.25 | 0.54 **(per 3 month)** | 0.00 |
| **Hatchling: H** | <30 | 1.00 | 0.38 **(year-1)** | 0.00 |
| **Juvenile: J** | 30-121 | 7.00 | 0.78 **(year-1)** | 0.00 |
| **Subadult: S** | 122-182 | 7.00 | 0.73 **(year-1)** | 0.00 |
| **Adult: A** | >183 | >30.00 | 0.83 **(year-1)** | 2.37 |
| **Southern Population** | | | | |
| **Egg: E** | 0 | 0.25 | 0.54 **(per 3 month)** | 0.00 |
| **Hatchling: H** | <30 | 1.00 | 0.38 **(year-1)** | 0.00 |
| **Juvenile: J** | 30-121 | 3.00 | 0.78 **(year-1)** | 0.00 |
| **Subadult: S** | 122-182 | 3.00\* | 0.73 **(year-1)** | 0.00 |
| **Adult: A** | >183 | >30.00 | 0.83 **(year-1)** | 5.98 |

\* Dunham et al. (2014) shows four years as the duration for subadult. However, we needed to change the duration to three years to make the results consistent with those presented in the paper.

Further details about the matrix model were not provided other than the Crouse et al. (1987) method for calculating the retention rate and transition rate in a stage-structured model was used. We constructed two matrices, one for each population to represent the original matrices described in the paper. The matrices constructed based on the descriptions in the paper resulted with a value in lambda of 0.87 for the northern population and 1.02 for the southern population, consistent with the values in the paper, with one modification that the duration in the subadult stage of the southern population was 3 years instead of 4 years. With this modification, both matrices also gave almost the same reproductive values and stable stage distributions listed in the paper. The matrix model in Dunham et al. (2014) is a five-stage model (*E*: egg; *H*: hatchling; J: juvenile; S: subadult; and A: adult) where a population matrix is given as:

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The values for these elements are shown in Table S4. We refer the original matrices for northern and southern populations are A1 and A5, respectively.

One of the major problems in the construction of the matrix was that the model assumed a post-breeding census, but the fecundity term did not include adult or egg survival. To correct for this, we reduced the number of stages from five to four so that the first stage is hatchling, and the fertility rate was modified to include the survival rates of the egg ( ) over three months and adult () over 9 months as  where  is the product of mean clutch size, sex ratio, and percent of females breeding. In addition, we also incorporated the fertility rate for the subadult stage as

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Incorporating the fertility rate for the subadult stage, we assume that individuals remain in the juvenile stage for seven years on average, but when they transition into adult stage, they also reproduce. A resulting population matrix is given as

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In this matrix, other elements (i.e. *P*’s and *G*’s) remain the same except their locations in the matrix were changed as shown in the matrix above. We refer the modified matrices for northern and southern populations as A2 and A6, respectively.

As discussed with the lionfish model, the method of Crouse et al. (1987) assumes that population growth rate *λ* to be 1. When the growth rate is far from 1, the survival rate in the transition calculation needs to be discounted with *λ.* The model with *λ* incorporated into the transition calculations (which affect , , , , and ) are referred as A3 and A7 for northern and southern populations, respectively.

Finally, the Leslie matrices were constructed for northern and southern populations using the same survival rate as the stage-structured models. The Leslie matrix for the northern population (A4) consists of 16 age classes, and that for southern population (A8) consists of eight age classes. For both models, adult stage and the last age class of subadult stage have positive fertility rate as where  denotes the age class of parents reproducing.

In total, eight models were constructed with A1, A2, A3, and A4 corresponding to the norther population and A5, A6, A7 and A8 corresponding to the southern population. Elements of the population matrices are shown in Table S4.

Table S. Elements of matrix population models for northern and southern alligator populations. Values are rounded values. To obtain exact values used in calculations, insert the parameter values in Table S3 into the notations shown in this table.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **North** | **South** | **Notation** | **North** | **South** | **Notation** | **North** | **South** | **Notation** |
| **Model** | **A1** | **A5** | **A1 & A5** | **A2** | **A6** | **A2 & A6** | **A3** | **A7** | **A3 & A7** |
|  | 0.54 | 0.54 |  | -- | -- | -- | -- | -- | -- |
|  | 0.38 | 0.38 |  | 0.38 | 0.38 |  | 0.38 | 0.38 |  |
|  | 0.73 | 0.58 |  | 0.73 | 0.58 |  | 0.71 | 0.59 |  |
|  | 0.047 | 0.20 |  | 0.047 | 0.20 |  | 0.074 | 0.19 |  |
|  | 0.70 | 0.56 |  | 0.70 | 0.56 |  | 0.68 | 0.56 |  |
|  | 0.034 | 0.17 |  | 0.034 | 0.17 |  | 0.054 | 0.17 |  |
|  | 0.83 | 0.83 |  | 0.83 | 0.83 |  | 0.83 | 0.83 |  |
|  | 0 | 0 | 0 | 0.046 | 0.600 |  | 0.075 | 0.579 |  |
|  | 2.37 | 5.98 |  | 1.11 | 2.81 |  | 1.11 | 2.81 |  |

Using the eight population matrices, asymptotic population growth rate λ (Figure S8), stable stage distribution (Figure S9), reproductive value (Figure S10), the sensitivity (Figure S11) and elasticity (Figure S12) of the population growth rate to stage specific survival rate and fecundity (*f*), damping ratio (Figure S13), and generation time (Figure S14) were calculated. To obtain λ under A3 and A7 using the iterative method, initial λ was set to 1. Reproductive values for all models were scaled so that the reproductive value of the hatchling stage is 1. For calculating the stable stage distribution and sensitivity under A4 and A8 for the hatchling and subadult stages, corresponding values for age-classes were summed. Similarly, reproductive values for these stages under A4 and A8 were calculating the weighted mean of reproductive values for corresponding age classes, where the weight is given by their stable stage distribution. For calculating the sensitivity of lambda under all stage structured models (i.e. except A4 and A8), numerical differentiation was used because juvenile survival appears in multiple elements of these matrices, and λ appears in multiple elements under A3 and A7. In this study, generation time was defined as the mean age of mothers and calculated using the formula in Bienvenu and Legendre (2015).



Figure S Asymptotic population growth rates of populations under A1-A8.



Figure S9. Stable stage distribution of hatchling, juvenile, subadult, and adult stages under the eight models A1-A8.



Figure S10. Reproductive value of juveniles, subadults and adults under the eight models A1-A8.



Figure S11. Sensitivity of lambda to stage-specific survival and fecundity. H: hatchling, J: juvenile, S: subadults, A: adults.



Figure S12. Elasticity of lambda to stage-specific survival and fecundity. H: hatchling, J: juvenile, S: subadults, A: adults



Figure S13. Damping ratio of populations under A1-A8.



Figure A14. Generation time of populations under A1-A8.

## Reference

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