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Sensitivity Analysis in Periodic Matrix Models: A Postscript to Caswell and Trevisan†

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Abstract—Periodic matrix population models are a useful approach to modelling cyclic variations in demographic rates. Caswell and Trevisan [1] introduced the perturbation analysis (sensitivities and elasticities) of the per-cycle population growth rate for such models. Although powerful, their method can be time-consuming when the dimension of the matrices is large or when cycles are composed of many phases. We present a more efficient method, based on a very simple matrix product. We compared the two methods for matrices of different sizes. We observed a reduction in calculation time on the order of 24% with the new method for a set of 26 within-year Leslie matrices of size 287 × 287. The time saving may become particularly significant when sensitivities are used in Monte Carlo or bootstrap simulations.

Keywords—Sensitivity, Elasticity, Periodic matrix models, Population dynamics, Population growth rate.

Periodic matrix population models are a useful approach to modelling cyclic variations in demographic rates, such as are caused by seasonality within the year or by interannual cyclic variability. See [2, Chapter 13] for a review of biological applications. Caswell and Trevisan [1]

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introduced the perturbation analysis (sensitivities and elasticities) of population growth rate for periodic models; the objective of our postscript is to introduce a simpler way to calculate these sensitivities and elasticities.

We suppose here that the cycle is composed of K "phases" (e.g., a year composed of $K = 4$ seasons, or of $K = 26$ two-week phases). The phases need not be of the same duration. The matrices $\mathbf{B}_1, \mathbf{B}_2, \dots, \mathbf{B}_K$ denote the population projection matrices for the different phases. That is, matrix $\mathbf{B}_i$ projects the population from phase i to phase $i+1$; the phases are cyclic, so that $\mathbf{B}_K$ projects the population from phase K back to phase 1. The starting point of the cycle is arbitrary. Consider a cycle starting at the beginning of phase k and let $\underline{\mathbf{x}}(t)$ denote the population state vector at time t. The dynamics over the whole cycle are given by [1]

$$\underline{\mathbf{x}}(t+K) = \mathbf{B}_{k-1}\mathbf{B}_{k-2}\dots\mathbf{B}_1\mathbf{B}_K\mathbf{B}_{K-1}\dots\mathbf{B}_k\underline{\mathbf{x}}(t), \tag{1}$$

$$\equiv \mathbf{A}_k\underline{\mathbf{x}}(t). \tag{2}$$

The asymptotic properties of such models have been described in Skellam [3] and Caswell [1,2,4]. Under weak conditions of primitivity, the asymptotic population growth rate λ (on the per-cycle scale) is the common dominant eigenvalue of the product-matrices $\mathbf{A}_k$ (all the $\mathbf{A}_k$ have the same eigenvalues).

Our concern here is to calculate the sensitivities of λ to changes in the entries of each of the matrices $\mathbf{B}_k$. Using the notation in [1], let $a_{ij}^{(k)}$ denote the (i,j) entry of the product-matrix $\mathbf{A}_k$ and S_{A_k} the sensitivity matrix of $\mathbf{A}_k$, i.e., the matrix whose (i,j) entry is the partial derivative $\frac{\partial\lambda}{\partial a_{ij}^{(k)}}$. This matrix can be calculated directly from the eigenvectors of $\mathbf{A}_k$, but because the entries of $\mathbf{A}_k$ are complicated combinations of the phase-specific demographic rates, these sensitivities are difficult to interpret. Of more interest is the sensitivity matrix S_{B_k} (the matrix whose (i,j) entry is the partial derivative $\frac{\partial\lambda}{\partial b_{ij}^{(k)}}$ where $b_{ij}^{(k)}$ denotes the (i,j) entry of $\mathbf{B}_k$). Caswell and Trevisan [1] showed that these sensitivity matrices are given by

$$\mathbf{S}_{\mathbf{B}_k} = (\mathbf{B}_{k-1}\mathbf{B}_{k-2}\dots\mathbf{B}_1\mathbf{B}_K\mathbf{B}_{K-1}\dots\mathbf{B}_{k+1})^\top\mathbf{S}_{\mathbf{A}_k} \qquad k = 1,\dots,K. \tag{3}$$

Equation (3) is powerful and easy to implement in appropriate software. However, it requires the calculation of K sensitivity matrices $\mathbf{S}_{\mathbf{A}_k}$. This calculation could become time-consuming when the dimension of matrices $\mathbf{B}_k$ is large and when there are many phases in the annual cycle. Next, we present a more efficient method.

Since the sensitivity $\frac{\partial\lambda}{\partial b_{ij}^{(k)}}$ is independent of which cyclic permutation of the $\mathbf{B}$ matrices is considered, we suppose here for notational simplicity, and without loss of generality, that the cyclic projection matrix is $\mathbf{A}_1 = \mathbf{B}_K\mathbf{B}_{K-1}\dots\mathbf{B}_1 \equiv \mathbf{A}$. The population growth rate λ can be seen as a composite function of the variables a_{mn} and $b_{ij}^{(k)}$, i.e.,

$$\lambda = \lambda\left(a_{mn}\left(b_{ij}^{(k)}\right)\right), \qquad i,j,m,n = 1,\dots,q; \quad k = 1,\dots,K, \tag{4}$$

where q is the dimension of matrices $\mathbf{A}_k$ and $\mathbf{B}_k$.

From the chain rule, the partial derivative of λ with respect to $b_{ij}^{(k)}$ is

$$\frac{\partial\lambda}{\partial b_{ij}^{(k)}} = \sum_{m,n}\frac{\partial\lambda}{\partial a_{mn}}\frac{\partial a_{mn}}{\partial b_{ij}^{(k)}}. \tag{5}$$

Our problem is to find the derivatives $\frac{\partial a_{mn}}{\partial b_{ij}^{(k)}}$ in a more efficient way than that of Caswell and Trevisan [1]. To do so, we rewrite matrix $\mathbf{A}$ as

$$\mathbf{A} = \mathbf{C}\mathbf{B}_k\mathbf{G}, \tag{6}$$