Invasive species management in two-patch environments: Agricultural damage control in the raccoon (*procyon lotor*) problem, Hokkaido, Japan

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The invasive species have increasingly been acknowledged as a global threat, since they could fundamentally destroy indigenous ecosystem after its establishment [8]. Many governmental attempts have been made to eradicate the established invasive species. Unfortunately, however, only a few succeeded, and most of them failed especially when the habitat is sufficiently large [2]. That is, the management official ends up halting eradication attempts [6, 2]. When the invasive species are widespread in a large habitat, then catchability could be decreasing in the invasive species stock. This implies that the cost of removing the last 1-10% population becomes prohibitively expensive, and thus achieving extermination appears to be extremely difficult [6, 2].

Given the historical fact, many researchers and practitioners sometimes recommend "area-wise control," which includes attempts for local extermination. Such regimes in invasive species management are that removal operations for invasive species are made only in some part of the whole habitat where some important industry or ecological asset is located such as agriculture. Whereas area-wise controls have recently emerged as a management scheme in invasive species management, a series of literature, which analyze the management strategy in this vein, mainly focus upon a situation where invasive species are reproduced and removals are implemented in a single closed system [4, 7]. However, such a framework is not appropriate for the type of problems in which removals efforts are locally implemented.

It is noted by several papers that a meta-population model is more appropriate since (i) local removals potentially impact the inter and intra species competition, and (ii) habitat conditions may simply be heterogenous [3, 5]. As a result, density dependent migration may become asymmetric [1]. Although there may be several works which consider area-wise controls, none of them, to the best of our knowledge, explicitly examine the effect of a meta-population structure, stock-dependent catchability and asymmetry in migration in the invasive species management. Thus this paper seeks to tackle these issues.

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The goal and contribution of this research are to develop a simple framework of discrete-time models for analyzing the long-run consequences of removal operations for a meta-population, and to answer several open questions in the context of invasive species management. In particular, an ecological model with two-patch environments is proposed, considering the key features of invasive species controls: (i) asymmetry in density dependent migration, and (ii) the effect of stock-dependent catchability.

The results suggest that the long run equilibrium is qualitatively affected by both the degree of asymmetric migration and the sensitivity of catchability in response to a change in the existing population of invasive species. Notable observations among the results are drawn as follows: 1. Local extermination is achieved if the sensitivity of catchability is sufficiently small. However, local extermination is not necessarily an economically best goal. This implies that even though local extermination is technically feasible, we must be cautious to set it as a social goal. 2. The degree of asymmetric migration impacts the long run equilibrium of ecological variables in the intuitive manner. On the contrary, it does not always impact an economically optimal effort level, that is, there exists a situation where an economically optimal effort level is independent of the degree of asymmetric migration. In fact, such a situation arises when an economically optimal effort level happens to be at the level at which invasive species are not exterminated, as well as when the sensitivity of catchability is sufficiently large.

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