C (1) List of Participants

Name: ***Graduate Degree Programs***	**IGERT contribution**
Raymond M. Newman: *Conservation Biology; Ecology, Evolution & Behavior; Water Resources Science* **(PI)**	Aquatic impacts and control
David A. Andow: *Entomology; Ecology, Evolution and Behavior; Conservation Biology; Sustainable Agriculture Systems* **(Co-PI)**	Risk analysis, resistance evolution
Susan M. Galatowitsch: *Applied Plant Sci.; Conservation Biology; Ecology, Evolution & Behavior; Water Res. Sci.* **(Co-PI)**	Restoration ecology; invasive spp. biology
Anne R. Kapuscinski: *Conservation Biology; Sci, Technology & Environmental Policy; Dev. Studies & Social Change;* **(Co-PI)**	Environmental risk analysis; fish GEOs
Ruth G. Shaw: *Ecology, Evolution & Behavior; Plant Biol. Sciences* **(Co-PI)**	Evolutionary genetics
Neil O. Anderson: *Applied Plant Sciences; Conservation Biology*	Invasive plant evolution; prevention of invasion
Gary Balas: *Control Sci. & Dynamic Syst.; Aerospace Engineering*	Risk Analysis
Robert G. Haight: *Cons. Bio.; Natural Resources Sci. & Manage.*	Risk analysis models
George E. Heimpel: *Entomology; Ecology, Evolution & Behavior*	Biological control, GEOs
Frances Homans: *Applied Economics; Cons. Bio.; Water Res. Sci.*	Risk analysis economics
Terrance M. Hurley: *Applied Economics*	Risk analysis economics
William Hutchison: *Entomology*	Decision analysis; insects; biocontrol
Nicholas R. Jordan: *Applied Plant Sciences; Conservation Biology; Sustainable Agriculture Systems*	Civic engagement; invasive weed species
Jennifer Kuzma: *Science, Technology & Environmental Policy; Public Policy; Public Affairs; Urban & Regional Planning*	Science technology policy
Kristen Nelson: *Conservation Biology; Natural Resources Sci. & Manage.; Dev. Studies & Social Change*	Conflict resolution; Deliberation
Karen S. Oberhauser: *Conservation Biology; Ecology, Evolution & Behavior; Biological Science*	Nontarget GEO impacts, insects
David W. Ragsdale: *Entomology*	Biocontrol: Insects/weeds
Mike Sadowsky: *Microbiology, Immunology and Cancer Biology; Microbial Ecology; Microbial Engineering; Soil Science*	Microbial ecology, GEOs, invasive microbes
Peter W. Sorensen: *Conservation Biology; Neuroscience; Ecology, Evolution & Behavior; Water Resources Science*	Aquatic invasive control
Robert C. Venette: *Entomology; Biological Science*	Invasion biology, risk assessment, biocontrol,

Additional faculty: (Department: Name)	
Agronomy Plant Genetics: Roger Becker, Don Wyse *Applied Economics:* Steve Polasky *Ecol., Evol. Behav.*: David Tilman. Diane Larson *Center for Teaching and Learning:* Valerie Ruhe, David Langley *Entomology:* Roger Moon, Vera Krischik *Fish, Wildl. & Cons Bio:* Doug Johnson *Forest Resources*: Lee Frelich, Rebecca Montgomery, Peter Reich	*Horticultural Science:* Mary Meyer, Alan Smith *Public Health:* John Adgate, Deborah Swackhamer *Rhetoric:* Daniel Philippon *Sociology:* Rachel Schurman *Statistics:* Gary Oehlert, Galin Jones, Sanford Weisberg *Veterinary Medicine:* Will Hueston

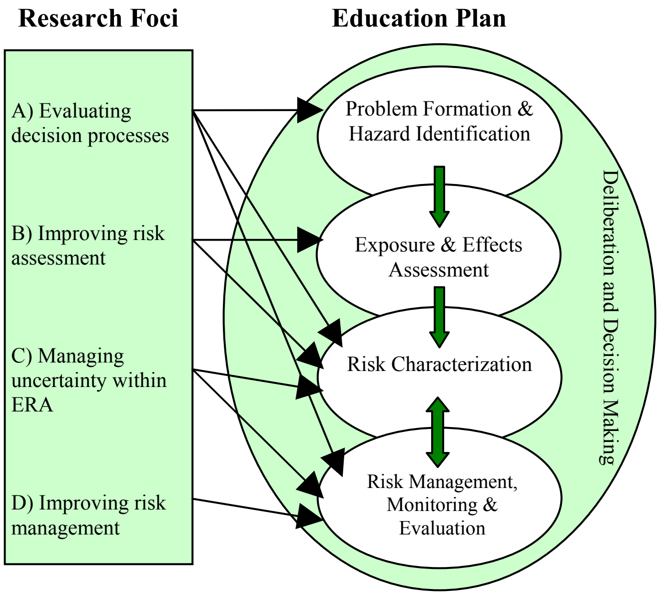
C (2) Vision, Goals and Thematic Basis

Globalization is driving an unprecedented number of introductions of exotic species and new genotypes into ecosystems. Although some of these introductions are purposeful, many are accidental. Outcomes of these introductions can range from highly beneficial to extremely damaging, with such judgments often depending upon how tradeoffs between potentially beneficial and detrimental effects are evaluated. Society desperately needs scientific leaders who excel at integrating fundamental science with consideration of societal factors in order to create better public policy and improve the scientific basis for risk analysis.

Similar ecological and evolutionary processes drive the establishment and spread of introduced species and genotypes (ISGs; Tiedje et al. 1989; Williamson 1996). These processes determine whether or not a *purposefully introduced* species becomes invasive, either as a pest within a managed system (e.g. agricultural fields, fish farms, or forests) or as a new biotic component in a natural ecosystem. They also influence whether *accidental introductions*, such as aquatic species hitchhiking on recreational and commercial vessels, remain innocuous or become highly invasive. Scientists need to understand these same processes to assess whether the purposeful introduction of *biological control agents* will effectively manage target organisms and how they may affect non-target organisms. Understanding these processes can also guide the design of genetically engineered organisms (GEOs) to reduce chances of their invasion or to help control invasive organisms via deliberate spread of detrimental genes. Comprehensive analysis of consequences of biological introductions for ecosystems and human communities requires integrating information from evolutionary and biological sciences with key areas of the social sciences.

The overarching goal of our IGERT program is to educate Ph.D. students to conduct research to improve Ecological Risk Analysis (ERA) and contribute workable solutions to policy questions and problems affecting management of introduced species and genotypes. Our IGERT program will use ERA as a conceptual framework for understanding ecological effects of invasive species, genetically engineered organisms, and biological control agents from a decision making perspective (Fig. 1). ERA was developed during the 1970s to address the environmental risks of chemical contaminants, such as pesticides, industrial wastes, and mine tailings. ERA has been supported by quantitative fate and transport models, which assess where and how long the environment is expected to be exposed to these chemical hazards. It also allows the quantitative assessment of the effects, which determines the expected harm from a given exposure to a chemical hazard. Concerns about exotic species and new genotypes arose later. However, it was quickly realized that because these organisms reproduce and evolve (Cox 2004), most quantitative methods developed for chemical hazards have limited applicability for ERA of biological introductions. Although this stimulated some development of ecological risk assessment tools (EPA 1999), in the U. S., ERA for invasive species continues to rely primarily

Fig 1. The educational plan utilizes four research foci (rectangle) that feed into improving ERA (large oval, after EPA 1999). The plan is organized around technical analysis, deliberation, and decision-making processes.



on qualitative expert judgment, while ERA for GEOs and biological control agents remains an ad hoc mixture of qualitative and quantitative methods. Thus, there is considerable room for improvement of ERA for biological introductions (Simberloff 2005).

Risk analyses have been done using two general, but often contrasting, models (NRC 1983, 1996). The 1983 model develops risk analysis as a technical process that can be divided into three interconnected parts: risk assessment, risk management and risk communication. It relies mostly on natural science information, and uses social science only to evaluate social and economic consequences of regulatory options at the end of the risk management phase. This limits multi-stakeholder input to formal public comment near the end of the decision process. This model has been modified for quantitative chemical risk assessment and, to a more limited extent, for ERA (EPA 1999). The 1996 model links scientific analysis and multi-stakeholder deliberation at key points throughout risk analysis. This allows the integration of expertise in the natural and social sciences to reach scientifically sound and broadly trusted decisions (e.g., Nelson et al. 2004). Whereas the 1983 model stresses objective features of ERA, the 1996 model emphasizes subjective ones; it measures and weighs environmental goods, representing the resolution of disparate environmental values held by different people. ***Our IGERT will utilize both of these general models to frame both our research and education components (Fig. 1), addressing the technical and deliberative demands of ERA.***

Our program will prepare students to apply scientific expertise to improve ERA of biological introductions. In our experience, ecologists, economists, and social scientists working with introduced organisms often lack adequate graduate training to apply science to solve real-world problems. Biology students typically have inadequate preparation to consider the societal and policy implications of scientific discoveries, whereas economists and social scientists often lack a fundamental understanding of ecological principles. The need to fill these training gaps is heightened by rapid developments in genetic engineering and biotechnology, concerns about invasive species and new genotypes, and increased levels of international commerce leading to increased rates of biological invasions (Mack et al. 2000).

We will address these training gaps by providing IGERT students with a program based on collaborative learning, coursework addressing the risk analysis processes and quantitative modeling, a problem-solving practicum providing experience with risk analysis problems in collaboration with national and international external partners, and a cooperative learning practicum whereby students will translate what they learned in the problem-solving practicum into teaching tools for the program and our external partners. Students will conduct research to improve the scientific basis for ERA decision making, considering how their research results can be used to improve the decision making process. They will have opportunities to conduct portions of their dissertation research off-campus with our external partners, including local as well as international institutions. Our proposed curriculum (see section C4) emphasizes collaborative learning that connects science to policy and society and focuses on establishing linkages between research and ERA decision-making.

The breadth of research expertise of our faculty and external partners (Table 1) promotes effective linkage among all phases of risk analysis (from risk assessment to management and deliberation) that pertain to the introduction of a wide range of exotic species and novel genotypes (microorganisms, plants, invertebrates and vertebrates). Our domestic and international partners offer unique educational opportunities for students; collaborations with partners will allow our students to deepen their understanding of how fundamental scientific knowledge can be brought to the interdisciplinary process of ERA.

C (3) Major Research Efforts

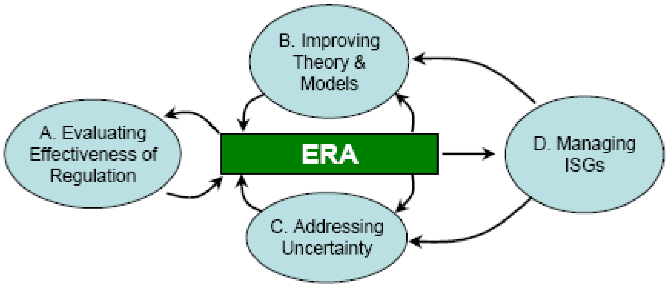
ERA leads to decisions to allow or disallow an activity, such as the deliberate introduction of an exotic species and, further, whether to require management to limit the consequences of introductions. Our research will focus on science that informs ERA in the context of the decision process that employs scientific models to assess and manage risk. Our students will conduct research to improve the scientific basis for decision-making and will examine how this scientific information filters through to improve these decisions.

Table 1. External partners who have committed to hosting IGERT students for problem solving practicums and/or dissertation research (*letters in Section H).

Organization, Location and Abbreviation	Educational Opportunities
North America	
CHS (formerly Cenex, Harvest States; MN)	See letter of support*
Center for Biological Control, Florida A&M Univ. (FAMU)	See letter of support*
General Mills (MN)	GEOs in food products
Minnesota Invasive Species Advisory Council (MISAC)	See letter of support *
Nat'l Research Council, Agric. & Natural Resour. (Wash., DC) (NRC)	ERA, policies for ISGs
United Nations, Convention on Biological Diversity (Montreal) (CBD)	Int'l ERA &ISG policy
U.S. Geological Survey (USGS)	Forest & rangeland ISGs
U.S. Fish and Wildlife Service (FWS)	See letter of support *
U.S. Forest Service (USFS)	See letter of support *
South America	
Embrapa (Brazilian Agricultural Research Corporation)	See letter of support *
Asia	
Burapha University (Chonburi, Thailand) (BU)	Fish ISGs
Chinese Academy of Agricultural Sciences (CAAS)	Biological control
Shanghai Fisheries University, Aquatic Genetic Resources Lab (SFU)	Aquatic ISGs
University of Tokyo (Tokyo and Komaba, Japan) (UT)	Plant invasion, GE crops
Yokahama Unversity (Yokahama, Japan) (YU)	See letter of support *
World Fish Center (Penang, Malaysia) (WFC)	See letter of support *
Europe	
CABI Bioscience (Delemont, CH) (CABI)	Biocontrol, plant invas.
European Biological Control Lab. of USDA (Montpelier, FR) (EBCL)	Biological control
Netherlands Institute of Ecology (Nieuwersluis, NL) (NIOO)	ERA of ISGs
Africa	
South Africa National Biodiversity Inst. (Cape Town) (SANBI)	See letter of support*
Center for Invasion Biology, Univ. of Stellenbosch (SA) (CIB)	Plant & animal invasion
Australia	
Australian Centre of Excellence for Risk Analysis (ACERA)	ERA for ISGs
CSIRO (Canberra and Hobart)	See letter of support*
Invasive Animal Coop. Research Centre (IA CRC)	ERA, biocontrol

We will improve ERA by evaluating its performance in assessing or managing specific risks. These evaluations will lead us to propose modifications to ERA associated with any of our four research themes (Fig. 2). For example, biological control of invasive purple loosestrife has succeeded in many wetlands but reed canarygrass, another invasive wetland plant, may then take over. Galatowitsch's research group developed a model based on Tilman's R* theory of plant competition (e.g., Tilman 1982) and designed experiments (Perry et al. 2004) to predict conditions that would constrain reed canarygrass growth. Management based on the experimental results verified model predictions. Another example is the risk that European corn borer will evolve resistance to transgenic Bt corn. Models

Figure 2. Organizational model for our IGERT research efforts, illustrating that our research themes are informed by an evaluation of ERA performance and that our research will help to improve ERA.



resulting from our NSF-funded biocomplexity research (Heimpel et al. 2005) and others (Gould 1998) predict that a refuge of non-Bt corn near pure Bt corn can reduce selection sufficiently to delay resistance evolution over 20 years. EPA has required the use of resistance management measures, and research to verify the models (e.g., Bourguet et al. 2003) is underway. In addition to studying such scientific aspects, we will improve ERA by integrating scientific findings with economic considerations and stakeholder deliberations within the risk assessment decision process.

Our IGERT will address four focal research themes (Fig 2). (A) Are the regulatory processes effective at allowing or excluding new species and genotypes appropriately? (B) Can risk assessment models be improved, and if so, when is this improvement of value? (C) How can uncertainty be addressed within ERA? (D) How can risk management be improved?

(A) Evaluating effectiveness of regulation using retrospective analysis

The goal in ERA of exotic species and new genotypes is to allow introductions that benefit society and pose little or no risk of environmental or economic harm, and to exclude introductions posing high risk. Yet policy and regulation vary considerably across groups of species and genotypes and among countries. Although some international treaties are beginning to standardize approaches, most notably the Convention on Biological Diversity's Cartagena Protocol on Biosafety (for GEOs), and the WTO Sanitary and Phytosanitary Agreement, the US oversight system remains a patchwork of approaches. Exotic species ERA is often based on qualitative expert opinion (Orr et al. 1993; RAM Committee 1998). ERAs are not even conducted for horticultural plants, aquarium trade, and pets (Mack et al. 2000; Reichard & White, 2001). GEO ERA relies on case-specific assessments (OSTP 1986), whereas biological control ERA considers only qualitative interpretation of host range assessments (van Driesche & Reardon 2004).

Shared characteristics of effective policies can be used to evaluate policies and regulation for ERA (O'Toole 2004; Ellefson 1992). These characteristics include clarity of intent, validity of inferences of cause and effect, and adequacy of resources to implement the policy and ensure compliance. Students will have the opportunity to advance understanding of how these characteristics and others lead to effective ERA regulation and policy formation. They may ask: how have prior policy design and implementation contributed to improvement in ERA across sectors? Have the regulatory systems strengthened decision-making? Have they been effective in excluding invasives? To what extent did they allow introductions that later became invasive?

We propose retrospective analyses to assess, for cases of *past introductions* with a well-documented history of spread, whether the application of *contemporary* regulations would have appropriately excluded harmful organisms and allowed benign organisms. Are there policies and regulations that would be more effective than contemporary ones (Table 2)? Are such policies and regulations practical and acceptable? Did science succeed in informing the cause-effect linkages in the policy? Did regulatory systems identify taxa that were invasive at the time of introduction and those that later became invasive? Should different taxa be regulated differently or can policies and regulations be unified? An interdisciplinary team of IGERT faculty and students will apply the relevant regulations to diverse, well-documented cases of deliberate and accidental introductions over the last century or longer. The breadth of our expertise allows us to compare different organismal groups, pathways of deliberate and accidental introduction, and to conduct economic analysis of alternative policies (Hurley 2005).

The analyses must include cases that exemplify the toughest challenges to decision- making. For instance, following some introductions, long lag times preceded population explosions and consequent harm, as in the cases of the Brazilian pepper tree in Florida, mitten crabs in England, purple loosestrife in N. America, and a wood-boring terrestrial isopod in California (Crooks & Soulé 1999). In some cases, the boom was followed by a steep decline of the invader (Simberloff & Gibbons 2004). For instance, recent evidence in Lake Victoria suggests that the Nile perch, implicated in the demise of numerous endemic fish species, is now declining, while certain native species are partially recovering (Balirwa et al. 2003).

Students will gain the background for conducting these analyses through a *Risk Analysis Survey Course* and semiannual IGERT symposia (see Education and Training section below). The course will offer an overview of contemporary regulation, in-depth study of some of the challenging cases, and basic tools for conducting economic and policy analysis of regulatory programs. The semiannual symposia will include focused presentations and discussions of specific regulations, comparative policy analysis, case histories of invasions and introductions, and economic analysis of policy. With this background, each student will conduct retrospective analyses as part of a practicum, as independent projects, or as a focal aspect of her/his dissertation. Our external partners offer many opportunities to develop case studies for testing and verifying the retrospective analyses.

Table 2. Possible examples for retrospective analysis of present US regulation

Group of Species or Genotypes	**Introduction Pathway**	**Present Federal Regulation***
Crop plants	Deliberate	None
Exotic plants	Accidental	Plant Protection Act
GE plants	Deliberate	Coordinated Framework
Arthropod plant pests	Accidental	Plant Protection Act
Biological control agents	Deliberate	Plant Protection Act
Aquaculture	Deliberate	Lacey, Endangered Species Acts
Exotic fish	Accidental	National Invasive Species Act
Aquarium & pet trade	Deliberate	None
Exotic birds	Deliberate/ Accidental	Migratory Bird Treaty Act
Commodity trade	Deliberate	Plant Protection Act

*Other federal and state policies/regulations may be involved, which our analyses will consider.

(B) Improving theory and models for ecological risk assessment

ERA models for exotic species, GEOs and biological control agents are sparingly quantitative and extremely diverse in degree of sophistication. In the USA, exotic species ERA generally relies on qualitative expert opinion whereas, for GEO ERA, models are more developed but vary from somewhat qualitative food web models to more quantitative migration-selection-population dynamics models (Table 3). Strategies for model construction range from induction from empirical results (e.g., arrival and establishment models) to derivation from well-established population genetic theory. This diversity of modeling schemes poses challenges that we will address during our IGERT (Table 3).

We illustrate some of these challenges below. To prepare to strengthen and unify theory, students will gain broad exposure to the diversity of existing models in a modeling workshop, a *Risk Analysis Survey* course and a modeling course. Several problems not yet proven amenable to modeling that is useful for ERA (e.g., delayed impacts, indirect effects) will be described in

Table 3. Illustrative models for quantifying ERA

Risk or Risk component	**Mathematical Biological Model**
Introduction (Arrival)	Propagule pressure (Sailer 1983) International trade (e.g., McAusland & Costello 2004, Knowler and Barbier 2005, Costello & McAusland 2003)
Establishment	Intrinsic growth rate (Crawley 1986) Climate matching (Sutherst 1989)
Spread	Reaction-diffusion models (Andow et al. 1990) Spatial optimal control over space (Sharov & Liebhold, 1998)
Ecological Impact	R* (Tilman 1982; Andow 1994; Murdoch & Briggs 1996)
Gene Flow	Migration-selection (Haygood et al. 2004) Net fitness-Trojan gene (Muir & Howard 2002)
Non-target Impacts	Dose-response (Suter et al. 2000)
Resistance Risk	Migration-selection and population dynamic (Hurley 2005; Alstad & Andow 1995)

the *Survey Course* and will serve as foci for discussions during the roundtables and symposia.

Introduction (Arrival). Existing models have considered the arrival process empirically, relying on known transport pathways and assuming the probability of arrival is proportional to propagule pressure (Sailer 1983). In fact, arrival may be a non-linear function of the number of propagules and depend on aggregation. Several more rigorously quantitative models of exotic species introductions assess marine species invasions via ballast water and shipping patterns (Hayes 2002a,b; Hayes & Silwa 2003) and may guide improvement of the mostly qualitative models.

Economists have begun to investigate how best to intervene when international trade increases the risk of invasions. For example, McAusland and Costello (2004) found that the threat of new invasions depends on the past trade level with a region and the past exposure to exotic species. Identifying the relative risk of trade partners based on these aspects and then targeting specific regions can reduce inefficiencies resulting from certain market-based mechanisms, such as non-specific tariffs. Knowler and Barbier (2005) have demonstrated that taxes can produce a socially optimal level of exotic plant imports. Costello and McAusland (2003) have shown that protectionism may not mitigate invasion risks, and failure to account for agricultural damages skews the interpretation of the efficacy of these mechanisms. Students will have the opportunity to explore how these and related models may link to biological models of the introduction process so that management of ISGs can be integrated economically into broader discussions about trade policy.

Establishment. The establishment process is modeled as a function of the intrinsic growth rate, r. If $r > 0$, establishment occurs, otherwise it does not (Crawley 1986). Climate matching is currently one of the main considerations in predicting r. Students will participate in discussions of additional ecological aspects to consider improving predictions of r in the new environment. An extensive literature notes characteristics associated with invasiveness (Crawley 1986), but most of these have little predictive value. We will hold taxon-specific discussions of organismal characteristics that may help predict r in new environments, and these characteristics will be evaluated systematically through literature reviews and experiments. The taxa we will examine include soil microbes, plants, insects and fish. Characteristics that prove useful may be incorporated into existing climate-matching models. A novel element of this work will be the cross-taxon comparisons that will become possible as students progress in their research.

Spread of introduced organisms and gene flow risks. Models of both spread and gene flow are based on reaction-diffusion and migration-selection models. Spread models have been improved via more realistic population growth components, such as Allee effects (Veit and Lewis 1996), and gene flow models via inclusion of spatially restricted dispersal (Andow and Zwahlen 2006). In addition, Sharov and Liebhold (1998) have emphasized how to use spread models to “slow the spread” of an invading species in an economically optimal way. As with establishment, however, ecological factors that affect the key parameters have not been incorporated into the models. For example, the shape of the dispersal kernel, the rate of population growth at low density, and the selective advantage of a rare trait are all affected by ecological factors, but these have not been incorporated into models, thereby limiting accuracy of prediction. One specific area for student research will be gene spread models based on sexual selection. These models have been used to model gene spread in fish (Muir & Howard 2002) and may be more widely applicable.

Direct ecological impacts. One of the most challenging aspects of invasion biology is to predict the ecological effects of a new species or genotype. Following taxon-specific models (Kolar & Lodge 2002), Tilman (2004) developed a model for plant invasions based on the ‘R*’ rule - a species (or genotype) that can persist at the lowest level of a limiting resource will displace other species or genotypes (Tilman 1982). Consistent with this model, Fargione et al. (2003) showed that plant species most strongly inhibited the establishment and growth of invading species with similar resource requirements. This experimentally observable R* can be used to predict the effects of introduced genotypes (Andow 1994) or the efficacy of biological control agents in suppressing pests, as in the case of the California red scale (Murdoch & Briggs 1996). We will encourage students to test and extend this theory in their own research.

Minimizing direct ecological impacts via design. Our students will investigate strategies to breed non-invasive horticultural crops and farmed fish to minimize potential ecological impacts. In breeding programs, selected traits that confer market value generally constitute the basis for domestication. It may be possible to establish a 'non-invasive crop ideotype' and breed against invasiveness (Anderson et al. 2006a). Invasion models that associate species traits to ecological impacts in heterogeneous environments (e.g., Tilman 2004) could inform breeding objectives. The net fitness-Trojan gene model (Muir and Howard 2002) offers another perspective on breeding objectives. Since breeding programs are long-term, IGERT students would conduct research on the design of non-invasive horticultural crops and fish with known invasive types, using field trials to evaluate invasion risk in multiple environments (Anderson et al. 2006b).

Non-target impacts and food webs. Assessment of harm to biological diversity is typically indirect, relying on indicators of potential harm (Andow & Hilbeck 2004). The use of indicators has a long history and has proven valuable in several cases (e.g., mayflies as indicators of acidification of streams), but it has little scientific support as it is applied to invasive species, biological control agents and GEOs, for which ERA should be case-specific (Tiedje et al. 1989). Alternatives, however, have not been fully developed and validated. This gap offers rich research opportunities for IGERT students. The Andow & Hilbeck (2004) model classifies biological diversity according to ecological function (e.g., herbivory). For each function, worst-case risks in the local environment are identified (e.g., increased crop losses from enhanced herbivory), and species that are most likely causes are identified and used to assess the risk. This model allocates effort to the most serious concerns, uses financial resources efficiently and allows flexibility in developing a strategy for assessing risk. Another kind of model quantifies the probability of harm to a particular non-target species that is of special concern. For example, IGERT students could further develop the quantitative monarch butterfly model (Oberhauser et al. 2001).

The integration of quantification into decision-making. Increased quantification may not improve social deliberation and decision-making unless it is done in an iterative, deliberative process that involves diverse stakeholders. Quantification could enrich the decision-making process by informing deliberation on comparative futures, whereas quantification might be ignored if it fails to clarify cause-effect linkages. A methodology to improve social deliberation is Problem Formulation and Options Assessment (PFOA) (Nelson et al. 2004). It establishes context for societal dialogue (Fischer 2003; Hajer and Wagenaar 2003) concerning a proposal to introduce a novel species or genotype, such as farming Bt maize in East Africa. This multi-stakeholder approach to deliberation offers a rational, science-driven planning process by which stakeholders can assess their needs, evaluate the risks related to various options, and recommend to decision-makers policies to reduce societal risks and to enhance the benefits of various options. Improved quantification, in conjunction with stakeholder conceptual models, offers the greatest potential for strengthening ERA and decision-making for biological safety. In our proposed *Risk Analysis Survey* course, students will learn how such an iterative approach can be used to improve outcomes and decision-making. Some may develop multi-stakeholder modeling components within their own research program.

(C) Addressing uncertainty in risk assessments

No risk analysis can be conducted with full scientific certainty (NRC 1983, 1996). Significant uncertainty arises from poor understanding of causal mechanisms in ecological systems and from limited data to describe components of a risk assessment model. For example, population growth rates are essential to characterizing population dynamics and spread rates (components of exposure assessment), but population growth has proven exceptionally difficult to predict for species introduced into new environments. Biologists often respond to this uncertainty by calling for more data. Student research within this theme will address three interrelated questions: (1) when does increased quantification enhance the value of risk assessments; (2) do different approaches for characterizing uncertainty lead to different risk management decisions; and (3) when does increased quantification reduce conflicts over risk management decisions?

Treatments of uncertainty in risk assessment vary. Expert judgments have figured extensively in qualitative risk assessments, but usually treat uncertainty in such general terms that it has little influence on risk characterization. In quantitative risk assessments, uncertainty has often been modeled with probability distributions. Farm-to-table risk assessments for food-borne hazards, such as *Salmonella enteridis* in eggs (Baker et al. 1998) and *E. coli* 0157:H7 in beef (USDA 2001), both involving Kuzma, have pioneered methods to account for limits of knowledge about model inputs in large food and agricultural systems. More recently, Bartell and Nair (2003) studied how narrowing the range of uncertainty for parameters would improve understanding of establishment risk of the Asian longhorned beetle. Economic modeling can enhance such analyses by assessing the value of reducing parameter uncertainty, for both biological and economic parameters. To be sure, uncertainty analysis is not always warranted, nor does it always lead to better management decisions (Paté-Cornell 2002), for example, when screening indicates the risk is below levels of concern, the cost of reducing exposure is low, or characterization of the nature and extent of the hazard is inadequate to permit even a bounding estimate (Hammonds et al. 1994).

An innovative aspect of our ERA research is the application of worst-case analysis tools (bounding assessments), which have been successfully used in engineering systems to elucidate their worst-case behavior, given modeling error, uncertainty and exogenous disturbances. These techniques can directly assess sensitivity of the results to individual model uncertainty and are less data intensive than probabilistic models, yet can better inform decision makers. For example, worst-case and probabilistic analysis applied to the NASA X-38 Crew Return Vehicle (Shin et al. 2001) prior to its first test flight revealed the effects of aerodynamic and mechanical model error on the performance of the vehicle. The probabilistic analysis methods failed to identify values of aerodynamic coefficients that would cause instability, whereas the worst-case analysis techniques successfully validated the flight control system *and* identified worst-case aerodynamic coefficients. Application to ERA will require refinement of quantitative ecological models and overall performance objectives for potentially affected ecosystems. Worst-case analysis would be used in concert with probabilistic analysis to clarify the role model parameters play in the analysis of such models as resistance evolution (Alstad & Andow 1995; Gould 1998), non-target effects (Andow & Hilbeck 2004), and net-fitness for assessing gene flow (Muir and Howard 2002).

A substantial economic literature on the value of information applies to the value of resolving uncertainty in parameters. Once quantitative models are developed and performance objectives are established, we can ask questions such as: is it preferable to devote research funds to learning about the effectiveness of control techniques or about the speed of an organism's spread? The key parameters of the model can be estimated from existing scientific knowledge, and uncertainty can be incorporated via probability distributions for those parameters. We will then assess possible scenarios, each with different parameter sets, to find the optimal course of action under each scenario. Under complete uncertainty, managers are assumed to follow a course of action where the control variables take on the expected value of the various optimal strategies. If the uncertainty is completely resolved, the control can be tailored to the true state of the world. The value of information can be calculated as the difference in expected value of overall benefits when parameter values are perfectly known at the outset versus when coefficients become known. Reduced variability in the parameters also has value and can be estimated (Bartell and Nair, 2004).

The PFOA methodology (Nelson et al. 2004, see C3B) recognizes that uncertainty can result not only from lack of scientific information, but also from lack of knowledge of individual and social values. By timely presentation of the best available scientific information to all stakeholders, PFOA reduces the misinformation and misinterpretation associated with conflict-ridden issues. It provides opportunity for discussion, leading to understanding of which values stakeholders share in common and those on which they differ. It also allows scientists to learn of concerns about the limits of scientific knowledge. IGERT students will learn about the full range of approaches to address uncertainty, both quantitative and qualitative, including worst-case analysis tools, optimization models, and multi-stakeholder deliberation.

A key strength of our IGERT faculty is its breadth of experience with regulatory agencies (e.g., EPA, USDA, FWS) and risk-assessment frameworks. Research groups will link risk assessors (Adgate, Andow, Hueston, Kapuscinski, Kuzma, Ragsdale, Venette), external partners (Table 1), economists (Haight, Homans, Hurley) and biologists with specialized expertise (Galatowitsch, Heimpel, Newman, Sadowsky, Shaw, Tilman). In their retrospective analyses of risk assessments (C3A, above), students will determine whether probabilistic methods or uncertainty analyses were employed and in what form(s). Uncertainty in the model and data will be quantified, when possible, for inclusion in models. Sociologists and governance specialists (Nelson, Schurman) will help structure social science questions about uncertainty in societal discourse, governance, and decision-making. Student teams will characterize the results of the risk assessments and evaluate how the public perceived the results. Finally, students will assess the role of uncertainty analysis in affecting the choice of risk management options.

These retrospective analyses will help IGERT students define appropriate ERA approaches (quantitative or qualitative) for their own studies. Where lack of information has prevented the past use of quantitative methods, students will work with faculty to design experiments to fill information gaps. For example, Venette prepared a qualitative assessment of the risks posed by a moth species, known only to occur in Mexico and South America (Venette & Gould 2006). Even in the face of extremely limited information about this species, this analysis revealed that this pest threatens US agriculture and ecosystems and warrants quarantine. Quantitative models were needed to evaluate the efficacy of potential quarantine treatments.

(D) Managing introduced species and genotypes and post-removal strategies: development of effective and environmentally sound responses

While the previous three research foci concern strategies to prevent invasions, the fourth emphasizes responses to invasions that have already occurred. Research to improve management of invasives is germane both to species that have invaded new environments and to GEOs that have escaped the habitats into which they were released.

Management options for invasive species and genotypes range from eradication and suppression to post-removal recovery and adaptive management designs. Some control strategies have been used to selectively eradicate insect and plant species, but selective eradication is rare for vertebrates. In many instances, the need for new approaches is pressing, both because nonselective toxicants are often the only available option and more generally, because new approaches could reinforce integrated pest management (IPM) strategies. Moreover, in some systems, complications arise because removal of introduced species can have adverse consequences (Zavaleta et al. 2001). Successful management of invasives can also hinge upon cooperation of the public. For instance, in areas where boaters are more willing to clean boats between lakes, invasive aquatics such as Eurasian water milfoil spread more slowly than in other areas. Further, local eradication of the invasive Asian longhorned beetle was achieved in Chicago but not New York, which differed in a combination of factors including local policy, funding, and behavior of the public (Antipin and Dilley 2004). Such cases highlight the fact that a comprehensive approach to managing invasives incorporates human behavior as a factor in understanding management efficacy (Nelson 2005).

Research of our IGERT faculty addresses four general issues of management: (1) new techniques for controlling and removing invasive species (Sorensen, Newman, Kapuscinski, Heimpel), as well as their ecological risks and feasibility (Kapuscinski & Patronski 2005; Heimpel et al. 2004), including the impact of human behavior and choice on control potential (Nelson 2005), (2) selective control methods (e.g., pheromones and natural enemies) to minimize risk to non-target organisms (Newman 2004, Sorensen & Stacy 2004), as well as inadvertent impacts of invasive species removal on non-target organisms (e.g., mortality from control agents or transfer of poisons through food chains, Andow & Hilbeck 2004; Heimpel et al. 2004), (3) the transition from removal to recovery (Perry et al. 2004; ; Galatowitsch and Richardson 2005), and (4) adaptive management systems for invasives. Managing the risks of control measures is an essential component of ERA, and IGERT faculty study selective control from the perspective of both controlling invasives and minimizing non-target risks.

Many of our research activities concerning risk management will employ an adaptive management framework. Adaptive management involves repeated cycles of program design, implementation, and evaluation, in a deliberate 'learn-as-you-go' approach. IGERT faculty currently employ this mode of applied research (e.g. Andow & Ives 2002; Kapuscinski 2002; Newman 2004; Jordan et al. 2005; Snow et al. 2005). Andow and Ives (2002) have outlined an adaptive system for managing the evolution of resistance to GE Bt crops, but these ideas have not yet been implemented. In another context, Jordan et al. (2005) have facilitated 'learning groups' for adaptive implementation of invasive management techniques in agroecosystems. Adaptive management has also been advocated for biological control, but has been implemented only rarely (Shea et al. 2002; Kapuscinski & Patronski 2005). Our IGERT faculty and students will synergistically develop adaptive management systems for diverse situations and determine the feasibility of their implementation. Dynamic management will serve as a common framework for addressing important management questions, including: Which species or genotypes of biological control agents provide the best control? What are the implications of differing spread rates and patterns for optimal management of invasive species or genotypes? How can evolution of resistance to a novel control measure be slowed? How will human behavior and preference influence the effectiveness of the control measures and be incorporated into management adaptation? Thus, IGERT students could participate in developing best management practices that maximize efficacy while minimizing risk to non-target organisms (Heimpel et al. 2004; Brown & Walker 2004; Sorensen & Stacey 2004). Current research of our IGERT faculty on invasive species management techniques includes biological control, genetic modification and pheromone release. Examples of systems available for this kind of research within our IGERT are managing leafy spurge in Great Plains grasslands, purple loosestrife in wetlands, aquatic weeds and sea lamprey in lakes, exotic carp in rivers, and soybean aphid and European corn borer in agricultural lands.

Problems of system recovery after removal or suppression of invasives are also of mutual concern. Several of our IGERT faculty (Galatowitsch, Jordan, Larson, Newman) work on post-removal restoration of ecosystems in which invasives have disrupted food-webs or altered soil microbial and nutrient dynamics. We will predict when post-removal restoration is likely to be necessary and determine the underlying mechanisms for different responses to removal. Major issues of common interest include roles of anthropogenic disturbance and forcing factors such as eutrophication, dispersal limitation, propagule depletion, and biotic-abiotic feedbacks that may operate in community assembly after removal, as well as feedbacks between human behavior and environment. We will develop modeling approaches for identifying appropriate removal strategies and post-removal management. In particular, we will address how the rate of removal affects restoration outcomes and how landscape context affects restoration success. IGERT students will have opportunities to work with our research partners in Japan (University of Tokyo) and South Africa (Center on Invasion Biology at University of Stellenbosch) to develop models for riparian corridors following invasive species removal.

All of the concepts of risk management outlined in this section will be covered in the general survey course, both as foci of lectures and discussions and embedded within case studies. In addition, IGERT fellows will have opportunities to apply these management methods in the practicums and in their dissertation work.

The proposed interdisciplinary investigation is an exciting opportunity for both the faculty and students in the IGERT program. The fruition of this collaboration will be to expose an entire new generation of researchers to new ideas to better understand and model ERA as well as to develop strategies to limit the effect on an ecosystem of introduced species or genotypes.