Biofuels and Invasive Species

Exploring the links between biofuel production systems and invasive species

A background paper prepared by John Mauremootoo for the IUCN Workshop on Biofuels and Invasive Species – Nairobi, Kenya, 20th-22nd April, 2009

Photo: David Chang

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Photo Credit: David Chang – *Arundo donax* (Giant Reed) being removed from a riverbank in California by the California Invasive Plant Council

1. Introduction

MOTIVATION BEHIND THE SEARCH FOR ALTERNATIVE SOURCES OF ENERGY

Increasing oil and gas prices, diminishing supplies of fossil fuels, a growing energy demand coupled with climate change and greenhouse gas emissions targets - as well as policies to promote rural development - have contributed to the reassessment of energy policy in countries worldwide, and the pursuit of alternative energy options.

While traditionally biomass is the energy option of more than 2.5 billion people worldwide, more advanced forms of bioenergy are being explored for power generation, and increasingly biomass is being converted into liquid fuels suitable for power motors, whether in stationary machinery or in vehicles, ships and aircraft.

The European Union, for example, has set a renewable fuels target of 10%, including a target of 5.75% of total transport fuel consumed by the end of 2010[1]. This target cannot be met without significant imports and so developing countries are increasingly being targeted as potential sources of land for biofuel export, by both public and private sector organisations. Many developing countries are also pursuing small-scale biofuel developments to improve access to energy in rural communities and reduce the burden of imported fossil fuels. Increasingly, the environmental, social and true greenhouse gas benefits of such initiatives is being brought into question and are being explored in the European Union and the Roundtable on Sustainable Biofuels, for example. Yet in such discussions, very little attention has been given to the plants used as biofuel feedstocks and the possibility that these plants, or the production systems of which they are part, could lead to invasive alien species (IAS) problems.

As background to the upcoming workshop on Biodiversity Risks of Biofuels[2] this paper will examine the invasive species risks posed by an expanding biofuel industry, through both the type of feedstock and the production methods chosen. It will also outline measures that could be used to mitigate these risks.

INVASIVE SPECIES AND THEIR IMPACTS

Introduced or alien species are the mainstay of our food production and forestry systems. Common food species, like rice, wheat, maize, chicken and cattle have been introduced around the world. Other alien species are used in forestry, landscaping, biological pest control, for sport, as pets and in food processing. A small proportion of alien species have become invasive, i.e. spreading extensively and causing major economic, environmental and health problems. Invasive species risks are increasing in line with growing and more rapid global travel and trade (Bright 1998, Mack *et al.* 2000). By one estimate, invasive alien species (IAS) cost the global economy $1.4 trillion per year which represents 5% of global production (Pimentel *et al.* 2001).

Invasive species can change recipient ecosystems through processes such as competition with resident species for resources such as space, light, nutrients and water; utilisation of resources previously unavailable to resident species; predation, parasitism or pathogenicity; interference with mutualisms such as pollination and by hybridisation with resident species. These ecological changes have the potential to negatively impact upon social, economic and environmental objectives such as the provision of adequate water supplies, the conservation and sustainable use of biodiversity and the use of land for leisure activities.

Although the vast majority of species classified as invasive are introduced, native species can become invasive in response to environmental changes (Howard and Chege 2007). For

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[1] Other targets can be viewed at http://www.bioenergywiki.net/index.php/Renewable_fuel_targets

[2] To be held at IUCN Nairobi, 20th to 22nd April, 2009

example, native acacia species have become invasive in various parts of Africa with changed grazing regimes, fire suppression or both (NARO 2007).

“Nativeness” is an ecological concept, so species that are native to a particular ecosystem in a country are not necessarily native to all ecosystems in that country. For example 21 of the species officially listed as invasive and noxious weeds in California are native to some of the lower 48 States but are not native to California. Evidently these species should be classified as alien species in California.

Another category that has sometimes been portrayed as a type of native invasion should more correctly be termed a “cryptic invasion”. In this case invasiveness can result from the introduction of new variety into previously non-invasive populations. For example, the explosion in the population of the common reed (*Phragmites australis*) in the USA in the last 150 years is probably due to an invasion of a non native variety that has both displaced native varieties and spread to areas not formerly occupied by the species (Simberloff 2008).

BIODIVERSITY IMPACTS

Invasive alien species cause more biodiversity loss than any other factor apart from habitat destruction (Wilcove *et al.* 1998). For example, introduced tree species such as pines and acacias had invaded two thirds of the *Fynbos* system in the Western Cape of South Africa before major control programmes were initiated, causing biodiversity losses as well as changes in ecosystem functioning and hydrology (Richardson *et al.* 1997). The cost to restore this system to its pristine condition was estimated to be $2 billion (Turpie and Heydenrych 2000).

AGRICULTURAL IMPACTS

Agricultural losses to IAS are enormous in all parts of the world. For example, the cassava mealybug (*Phenacoccus manihoti*) was accidentally introduced to the Democratic Republic of Congo in 1973. It rapidly spread causing yield losses of over 80% with an estimated cost to smallholders and subsistence farmers of $4.5 billion (Zeddies *et al.* 2001). A biological control programme using an insect parasite specific to the mealybug (a deliberate invasion to reduce the impact of an invasive species) succeeded in sustainably controlling the mealybug at an estimated cost of $27 million with no adverse environmental impacts. The cost of IAS to agriculture in the USA alone has been estimated to be $77.8 billion per year (figures extracted from Pimentel *et al.* 2005).

STRUCTURE OF THIS BACKGROUND PAPER

This narrative begins with an outline of the invasion process, from species introduction to invasion. It then goes on to examine some of the factors that contribute to species invasiveness and system invasibility and the links between these factors and invasion species risks associated with biofuel feedstock production systems. The paper then considers the invasion risks from first, second and third generation biofuel feedstock species and the systems of which they are part. Finally, invasive species management actions - prevention, early detection and rapid response, eradication, containment, control and ecosystem restoration - are examined as possible means of mitigating the invasive species risks associated with biofuel production systems.

The principal emphasis in this paper is on invasive plants, as the risk of plant invasion is the most striking invasive species consequence of an expanding biofuel industry. However, biofuel feedstock production systems can lead to additional invasive species risks such as the introduction of pathogens and insect pests. These risks are also outlined in this paper.

2. The Invasion Process

Invasive species pathways and vectors

Invasive species can be introduced intentionally or unintentionally. The means or route by which a species is moved from one location to another is known as the invasion pathway. This term covers both physical routes such as shipping and air transport networks, and activities which result in species movement such as trade in used car parts, trade in forest products and tourism. Biofuel feedstock production systems could constitute an invasive species pathway.

Vectors are the means by which a species can move along a pathway. A vector along the used car part trade pathway could be used tyres which can serve as breeding (and transport) habitats for mosquitoes. A vector along the forest products trade pathway could be timber which is infected by wood boring beetles. The tourist who smuggles plant material back home after their holiday acts as a vector along the tourism pathway. The person who imports a potentially invasive plant for use as a biofuel feedstock acts as a vector along the biofuel pathway.

The majority of invasive plant species have been deliberate introductions

Stages of invasion and lag phases

A biological invasion can be divided into three nested initial stages: (1) *Introduction* – species brought into the country but under containment, (2) *establishment* – species found in the wild (species sometimes known as *casual*) and (3) *spread* – species forming self-sustaining and spreading populations. If the spread then results in negative impacts to ecosystems, biodiversity or human health, development or livelihoods, it is considered as having become ***invasive.***

Some species, for example musk rats in Europe, Africanised bees in the Americas and many species of water weeds in Africa, go through the stages of establishment to biological invasion very quickly but many other species experience a distinct time lag between introduction and spread. These lags may be inherent, due to or caused by:

- the nature of population growth;
- ecological changes that favour the introduced species including factors such as climate change (Walther *et al.* 2002);
- the delayed arrival of mutualists (Richardson *et al.* 2000);,
- a new disturbance regime (Beauchamp and Stromberg 2007); and,
- genetic changes that improve the fitness of the introduced species in its new environment (Hobbs and Humphries 1995, Kowarik 1995, Crooks and Soulé 1999).

Lag times quoted in the literature for invasive plants are extremely variable. Analyses of historic data for plants imported into Europe have estimated average lag times between introduction and first evidence of spread to be 170 years for trees and 131 years for shrubs (Kowarik 1995). These figures may have been over-estimates because the plant might have been spreading for some time before its presence was recorded. Daehler (2009), using direct estimates from annual records from Hawaii, estimated average time lags of only 14 years for woody species and 5 years for herbaceous plants indicating that tropical plant invaders may have much shorter lag phases than temperate species.

The existence of lag phases illustrates the need for caution when categorising species as being non-invasive when they have only recently been introduced to a recipient ecosystem.

THE LIKELIHOOD OF AN INTRODUCED SPECIES BECOMING INVASIVE

For a variety of groups of animals and plants introduced to the United Kingdom, Williamson and Fitter (1996) estimated that approximately 10% of introduced species will become established and approximately 10% of these will 'spread to become pests'. Nonindigenous plants in different parts of the world vary in the degree to which they strictly adhere to this "tens rule" (e.g. Lockwood *et al.* 2001) but the point remains that only a small percentage of introduced species will go on to become invasive. However, this statement does not help us to predict which species are likely to become invasive.

3. Causes of Invasion Success – Why some species become invasive and some ecosystems become invaded

Scientist have attempted to explain biological invasions by identifying the traits of species that make them invasive (*invasiveness*), the characteristics of recipient ecosystems that make them vulnerable to invasion (*invasibility*) and historical factors (introduction effort and time since introduction) that facilitate invasion.

There is no universal trait that can be used to predict whether a particular plant will invade a particular ecosystem but there are at least certain factors that appear to render a plant species more or less likely to invade a recipient ecosystem. These factors have been used as the building blocks for the production of risk assessment tools to screen for invasiveness of proposed introductions (Kolar and Lodge 2001). These tools can help to identify the small fraction of species that could go on to become invasive, reducing costs of invasions by preventing importation. A summary of some of the factors that appear to facilitate plant invasions and their relevance to biofuel feedstock species is given below.

There is no universal trait that can be used to predict whether a particular plant will invade

TRAITS OF INVASIVE PLANTS

INVASION SUCCESS ELSEWHERE

It is often stated that the best predictor of invasiveness in a recipient ecosystem is the species' record as an invasive species elsewhere (e.g. Panetta 1993, Scott and Panetta 1993, Mack 1996, Reichard and Hamilton 1997, Caley and Kuhnert 2006). Though apparently self-evident, this statement does indicate that a good invader possesses traits that make it successful across a wide range of sites. With this information it should be possible to reject imports of potentially invasive species (prevention) and prioritise control for already established plants (early detection and rapid response, containment and long-term control). Proposals for the use of species with a history of invasion as biofuel crops should be treated with extreme caution and should consider mitigation measures. For example, jatropha *gossypifolia* was banned in Western Australia as invasive which raised alarm bells world wide when jatropha *curcas* started to be promoted as a potential biodiesel feedstock, though this is a different variety.

Of course *invasiveness elsewhere* is irrelevant if the species in question has no prior history of introduction or the previous invasions were in very different ecosystems with regard to ambient temperatures, humidity, rainfall, soil types, etc.

TAXONOMY
Some taxa may have common life history traits that make them good invaders. The following families appear to be consistently over-represented in terms of relative numbers of invasive species: Amaranthaceae, Brassicaceae, Chenopodiaceae, Fabaceae, Hydrocharitaceae, Papaveraceae, Poaceae and Polygonaceae (Rejmánek 2000). A number of grass species (Poaceae), several of which are known to be invasive in some systems, are being considered as promising biofuel crops (Raghu *et al.* 2006).

ABUNDANCE AND DOMINANCE IN NATIVE RANGES AND BROAD HABITAT TOLERANCE
Widely distributed species are likely to be invasive in their introduced range for two reasons. First, wider-ranging species are more likely to come into contact and be carried with international transport of goods. Second, species with larger original ranges are more likely to be pre-adapted to conditions in a new area (Scott & Panetta 1993, Rejmánek 1995, Goodwin et al 1999, Cadotte *et al.* 2006).

Invasive species are often habitat generalists, meaning that they are tolerant of a wide range of environmental conditions. Several studies have compared closely related species and found that the most invasive species were the ones capable of performing well under the broadest range of habitat conditions (Marvier *et al.* 2004).

Invasive species are often habitat generalists

Adaptability and broad habitat tolerance are likely to be attractive traits when considering a potential biofuel feedstock species.

HIGH RELATIVE GROWTH RATE AND EARLY MATURATION
Several studies have found that many invasive species have higher relative growth rates (RGR) than similar non-invasive species. Pattison *et al*. (1998) found that invasive rainforest plants had higher RGR than their native ecological equivalents in Hawaii. Similarly, Williams and Baruch (2000) reported that several species of invasive African grasses had higher RGR than native New World grasses. Grotkopp *et al.* (2002) found that RGR was positively correlated with measures of invasiveness in a range of pine species.

Other things being equal, plants that produce fruits, seeds or other propagules early in their development will be capable of relatively high reproductive rates, facilitating invasion (Rejmánek & Richardson 1996, Williamson and Fitter 1996).

High RGR is a desirable trait in biofuel crops as is early propagule production if the propagule is specifically used in biofuel production as is the case for the production of biodiesel from oilseed.

RELATIVELY LARGE SEED MASS AND FREQUENT SEED CROPS
Invasive species tend to have larger seeds and greater seed masses than closely related non-invaders (Daws *et al.* 2007). Rejmánek and Richardson (1996) also found that larger seed mass was related to invasiveness in the Pinaceae but for this family it was species with smaller seeds that tended to be more invasive. Frequency of seed crops is related to propagule pressure (discussed below) which is associated with invasiveness. Large seed masses and frequent seed crops are attractive traits in oilseed species. Other things being equal, large seeds are likely to be easier to harvest than small seeds but small seeded species, such as oilseed rape (canola), can be valuable biofuel crops if efficient harvesting techniques are available or can be developed.

VEGETATIVE REPRODUCTION
Vegetative reproduction, the ability to produce another plant asexually through structures such as rhizomes, roots, bulbs or tubers, can facilitate rapid spread and has been associated with invasive species (Reichard and Hamilton 1997, Burns 2006). Many of the species that have

been selected as promising biofuel crops can reproduce vegetatively as this may facilitate agronomic procedures and prevent the need for seed production and harvesting while retaining the same phenotype.

TRAITS OF INVASIBLE ECOSYSTEMS

ECOSYSTEM DISTURBANCE

The vast majority of plant invasions take place in human- and /or naturally-disturbed habitats (Rejmánek 1989, 1996, Hobbs 1991, Whitmore 1991). Disturbance, for example through fire, logging and overgrazing, releases resources that are available to new organisms and creates micro-sites for colonisation (Seabloom *et al.* 2003). The action of an invasive species is itself a form of ecosystem disturbance which, in certain instances, can lead to *invasional meltdown* - unpredictable accelerated impacts following multiple species introductions (Simberloff and Von Holle 1999).

To minimise environmental and food security risks, disturbed habitats, notably degraded and marginal lands, are among the principal target areas for biofuel crop production in many countries (Rajagopal 2008, Gopalakrishnan *et al.* 2008).

LACK OF PREDATORS, PARASITES AND PATHOGENS IN THE RECIPIENT ECOSYSTEM

The enemy release hypothesis (Keane and Crawley 2002) states that one of the reasons why invasive species are more competitive in their new environment is that they suffer less from natural enemies (predators, parasites and pathogens) than they do in their native range. For example Mitchell and Power (2003) studied viruses and rust, smut and powdery mildew fungi that infect 473 European plant species naturalised in the United States. On average, 84% fewer fungi and 24% fewer virus species infected each plant species in its naturalised range compared with its native range. Absence or rarity of pests is an attractive feature for any agronomic venture and biofuel production systems are no exception.

ECOLOGICAL DISTINCTIVENESS

Ecological distinctiveness, that is clear differences between the attributes of introduced and native species, appears to facilitate invasion (Williamson 1996, Ricciardi and Atkinson 2004). Ecologically distinctive species might be able to exploit a resource that is not being utilised by native species (Lockwood *et al.* 2001). For example the lack of large native floating aquatic plants in African freshwater systems may have facilitated the invasion of these systems by Neotropical water weeds (Howard and Chege 2007). A more subtle contrast, the fire-enhancing properties of Old World grasses, is likely to have resulted in intense fires that damaged and killed their New World counterparts contributing to the dominance of Old World grasses in many New World grassland ecosystems (Simberloff and Von Holle 1999). The introduction of an ecologically distinct biofuel feedstock species may, therefore, constitute an invasion risk.

HISTORICAL FACTORS THAT AFFECT INVASION SUCCESS

INTRODUCTION EFFORT OR PROPAGULE PRESSURE

Propagule pressure, sometimes also known as “introduction effort”, refers to the number of non-native individuals or propagules introduced to the recipient ecosystem and the number of release events. Propagule pressure is both a product of introduction history (number of introductions and their intensity) and biology (fecundity). Studies on a variety of taxa from a range of ecosystems worldwide consistently indicate that propagule pressure is one of the best predictors of successful establishment of non-native species (Lonsdale 1999, Kolar & Lodge 2001, Fine 2004). Extensive planting of non-sterile biofuel crops will intensify propagule pressure, which if accompanied by effective dispersal mechanisms will increase the chances of invasion of high-risk species.

TIME SINCE INTRODUCTION

The idea that the longer the time since introduction, the more likely it is that a species will become invasive is linked to the notion of lag times and propagule pressure. Evidence to support this idea, however, is inconsistent. Scott and Panetta (1993) found invasiveness to be greater for longer-established plant species in Australia. In contrast Carpenter and Cappuccino (2005) in a study in Ottawa, Canada, found that recently arrived plants tended to be more invasive than older introductions. Time since introduction alone, therefore is difficult to use as a predictor of invasion success for introduced plants – including biofuel feedstock species.

4. Potential Invasions of Plants in and around Biofuel Production Systems

FIRST GENERATION BIOFUEL FEEDSTOCKS

First generation (1G) biofuels are biofuels produced from existing food and feed crops using simple and well established processing technologies. Nearly all biofuels are currently 1G. Biodiesel is derived from plant oils such as rapeseed, palm oil and soy and bioethanol is a petrol replacement produced from sugar or starch crops such as sugarcane, sugarbeet, maize and wheat.

1G BIOFUEL CROPS - TRADITIONAL ANNUAL FOOD CROPS

Traditional food crops grown for ethanol (e.g. sugarcane, soya and maize) and biodiesel (e.g. sunflower and peanuts) have been selected to respond to high inputs of water, fertiliser and pesticides and typically grow on prime agricultural land. These highly domesticated annual crops are dependent on human activities and are unlikely to become invasive (Baker 1974).

Some other cultivated plants such as oilseed rape (*Brassica napus*) and sunflower (*Helianthus annuus*) are closely related to weedy species. It is conceivable that certain kinds of genetic modifications of such species might cause invasiveness (Keeler, 1989). Many candidate biofuel feedstocks are the focus of well-funded genetic modification programmes (Burke 2007). Genetic modification of crop plants, either by traditional or molecular techniques, has rarely resulted in them becoming invasive because most modifications have been for traits such as genetic uniformity for ease of harvest, high fertiliser and irrigation uptake, and low seed dormancy (DiTomaso *et al.* 2007). In contrast, biofuel feedstocks are being modified to increase their environmental range (through traits such as drought or salt tolerance and enhanced nutrient-use efficiency) and aboveground biomass, both of which could increase invasiveness.

1G BIOFUEL CROPS - PERENNIAL OILSEED CROPS

The most widely promoted perennial biodiesel feedstock plant is the African oil palm (*Elaeis guineensis*). Palm oil is the second most traded oil crop in the world after soy and the establishment of oil palm plantations is already a major cause of tropical rainforest clearance. A great deal of concern has been expressed that increased demand for oil palm as a biofuel crop would accelerate this process (Fitzherbert *et al.* 2008). Oil palm, with its large fleshy seeds which are dispersed by mammals and large birds, has become invasive in the Atlantic forest in Brazil (Howard and Ziller 2008).

Concerns about rainforest clearance and as well as the possible adverse impacts on food production and poor net carbon benefits of input-intensive biofuel production systems (Pimentel and Patzek 2005) have been among the motivations behind efforts to find feedstocks that can be grown on agriculturally marginal land using minimal external inputs while producing large annual yields (Farrell 2006). A number of oil producing trees and shrubs that appear to fit the above criteria are now being promoted widely including the following listed by

Low and Booth (2007): jatropha (*Jatropha curcas*), Chinese tallow tree (*Triadica sebifera*), neem (*Azadirachta indica*), olive (*Olea europaea*), castor oil plant (*Ricinis communis*), Chinese apple (*Zizyphus mauritiana*), moringa (*Moringa pterygosperma*), calotrope (*Calotropis procera*), giant milkweed (*Calotropis gigantea*), caper spurge (*Euphorbia lathyris*) and pongamia (*Milletia pinnata*).

With the exception of pongamia, all of these species are known to be invasive somewhere in the world. Other traits of these species that make them high risk include rapid growth and establishment rates, large propagule production, broad environmental tolerance and few natural enemies in the recipient ecosystems. The scale of many proposed planting schemes is likely to exert major propagule pressure increasing the risk of invasions on adjacent protected areas, forests and agricultural land.

Jatropha and Jatropha *curcas* in particular has been heavily promoted in many countries as a source of biodiesel, especially in developing country contexts.. For example, by 2012, under an official biofuel development strategy, India aims to have planted jatropha on about 13.4 million ha of land classified as marginal (GoI 2003). This represents an area slightly larger than the size of Greece.

Second generation biofuel feedstocks

Second generation (2G) biofuels are produced from a wider range of cellulosic biomass including agricultural wastes and plant species grown specifically for their biomass and converted to biofuels using advanced thermo-chemical or bio-chemical processes. A great deal of excitement is being generated by the prospect of 2G biofuels. Not only are they more efficient in terms of energy generated per hectare and equivalent greenhouse gas emission reduction, they open up the possibility of utilising a wide range of feedstock plants adapted to a range of environments, of utilising more marginal land for biofuel feedstock production, flexible harvesting times and the prospect of integrating biomass production into sustainable forest management practices. 2G conversion technologies are not yet commercially viable but costs are declining. The U.S. DOE estimates “that improvements to enzymatic hydrolysis could eventually bring the cost to less than 5¢ per gallon, but this may still be a decade or more away” (International Food and Agricultural Trade Policy Council 2006).

2G Biofuel crops - Planted Monocultures

In principle any plant species, including those growing in non-cultivated systems, could be used for the production of biofuel from lignocellulose - should the technology be successfully developed. In practice the likely second generation feedstock candidates will be those that can exhibit rapid growth rates and large biomass accumulation, ideally on agriculturally marginal land and with few external inputs. A variety of species, mainly grasses and woody plants are being considered.

Many of the leading candidates are perennial grasses that are mostly non-native to the proposed area of production (Lewandowski *et al.* 2000). As with the proposed new perennial oilseed crops, many of the grasses proposed as second generation biofuel feedstocks such as giant reed (*Arundo donax*), switchgrass (*Panicum virgatum*), reed canary grass (*Phalaris arundinacea*) and cord-grass (*Spartina* species) have a history of invasiveness elsewhere. The highly invasive *Spartina anglica*, first recorded in Southern Britain in 1892 (Gray *et al.* 1991), is a fertile polyploid (species with one or more extra sets of chromosomes) resulting from a spontaneous mutation in *Spartina x townsendii* which in turn is a sterile hybrid from a cross between the North American smooth cord-grass (*Spartina alterniflora*) and the native small cord-grass (*Spartina maritime*). Such complex and unexpected outcomes illustrate the need for caution when introducing species outside their native ranges.

Traits of some of the aforementioned species: perennial habit, rapid growth, efficient vegetative reproduction and absence of major pests or disease load resemble those of many grasses (included some of those listed above) which have been introduced for livestock forage or for erosion control and have gone on to become invasive (Barney and DiTomaso 2008). Species such as johnsongrass (*Sorghum halepense*) in the USA and false citronella (*Cymbopogon nardus*) in Uganda (CSF 2006) followed a sequence of selection and breeding for horticultural, agronomic, or erosion control purposes, cultivation in a recipient ecosystem, followed by escape and subsequent environmental or economic calamity (Reichard and White 2001, Simberloff 2008). This sequence has been repeated for other erosion control introductions such as kudzu (*Pueraria montana* var. *lobata*) and agroforestry introductions such as willows (*Salix* species) and poplars (*Populus* species). These agroforestry trees are now among those being widely promoted as second generation biofuel feedstocks, mostly in non-native ecosystems (Low and Booth 2007).

The risk of creating a biological invasion problem can be especially high when an agricultural enterprise is speculative. Second generation biofuel production systems exhibit the characteristics of speculative agricultural enterprises: for example explosive growth of interest, impressive promises, uncertain technology and dependence on subsidies. Lowe and Booth (2007) compare the current push for expanded biofuel crop production with the promotion of deer farming as a highly profitable venture in Australia in the 1970s. When promised profits failed to materialise and the market for deer crashed in the 1990s many deer farming projects were abandoned. Australia now has a fast growing feral deer problem as a result.

Another example of failed speculative enterprises resulting in invasive species problems is the introduction of the fast growing tree *Broussonetia papyrifera* (paper mulberry) to Ghana and Uganda to evaluate its potential for pulp and paper production. In both instances trial plantations were abandoned and no efforts were made to remove the paper mulberry trees. The species has now become an invasive plant degrading protected areas and cropping systems with severe economic consequences (Bosu and Apetorgbor 2007, NARO 2007).

2G BIOFUEL CROPS - HIGH DIVERSITY PLANTATIONS

The implicit aim of much of the research on biofuel feedstocks to date has been the creation of a low diversity cropping systems. However, in principle 2G feedstocks can be a mixture of diverse species. Tilman *et al.* (2006) planted combinations of 1, 2, 4, 8, or 16 perennial native herbaceous grassland species in an experimental low input system in degraded and abandoned agricultural land in Minnesota USA. A decade after planting 2-, 4-, 8-, and 16-species plots produced 84%, 100%, 157%, and 238% more bioenergy, respectively, than did those planted with single species. This approach holds great promise if the species are chosen carefully as they were in Tilman *et al.*'s experiments.

2G BIOFUEL CROPS - ESTABLISHED INVASIVE PLANTS

The fact that simple biomass is the raw material for 2G biofuels raises the possibility of using invasive species as a biofuel feedstock after they have been removed during ecosystem restoration programmes thus recovering some of the management costs (Biomass Research and Development Board 2008). However, there is the possibility that putting a market value on a species invasion will create an incentive for its further dissemination. If utilisation as a management option is to have positive invasive species outcomes, therefore, it must be part of an integrated approach that includes sustained control and other landscape management measures such as replanting with native species. This type of approach, where cleared wood has been utilised and wood products marketed, as part of an integrated invasive species management system, has been pioneered in the South African Working for Water Programme that clears woody invasive species from catchments and riparian zones to restore hydrological and fire regimes, the productive potential of land and biodiversity (Pierce *et al.* 2002).

Third generation biofuel feedstocks

Third generation (3G) biofuels are potential future biofuels produced from "energy-designed" feedstocks with much higher production and conversion efficiencies than other biofuels. One promising line of research is to reengineer easily cultured organisms such as the bacterium *E. coli*, yeast and algae to convert sugars from agricultural waste and other cellulosic materials to compounds that are essentially identical to today's fossil fuels. Other research efforts are focusing on engineering algae so that they can absorb sunlight to produce fuel directly.

Even if the technology to convert sugars and biomass to biofuels using reengineered organisms becomes economically viable in the near future, it will still largely depend on cropping systems to generate sugar and biomass. The invasive species implications of an emerging 3G biofuel industry are, therefore, likely to be similar to those outlined above for 1G and 2G technologies. Should the production of biofuel directly from algae become economically viable, it is likely to result in the proliferation of algal cultures. The environmental implications will depend on whether the algae is cultivated in shallow ponds or containers, in the open or in enclosed facilities, on-shore or off-shore. However it is a little speculative to investigate these in detail at present.

5. Species Invasions Associated with Biofuel Production Systems

Contaminated seed

The majority of invasive plant species have been deliberate introductions (Simberloff 2008). This is particularly the case for woody weeds (Reichard 1997). However, accidental introduction of plants as hitchhikers that have been transported in various ways is also a significant source of invasive species. Large numbers of herbaceous invasive species, in particular, have been introduced through contaminated crop seed (Baker 1986). A batch of seed may also be contaminated with insect pests and pathogens. The establishment of large biofuel crop production systems is likely to involve considerable movement of propagation material which poses a biosecurity risk. Clearly it is imperative that international standards for trade in plants and plant products are followed to mimimise this risk.

Fortunately, the International Plant Protection Convention (IPPC), the international treaty to secure action to prevent the introduction and spread of pests of plants and plant products, has laid down very clear guidelines (International Standards for Phytosanitary Measures) to ensure that traded plants or plant products are free of pests. However, actual implementation of the guidelines varies worldwide.

Pests of biofuel feedstocks

Traditional crop and forestry species grown as biofuel feedstocks will be exposed to the prevailing threats from pests and diseases. Standard pest management practices can be utilised to address these threats.

In addition, an expanding biofuel industry could accentuate pest and disease risks at the landscape level as many biofuel crops, notably grasses, can act as alternative hosts for common pests of crop plants. For example, insect pests of maize, sugarcane, and rice are known to feed on *Miscanthus* spp. (Brown *et al.* 2008). Area-wide pest control strategies may be required to reduce the impacts of pest movements between crops.

As previously stated, novel biofuel crops are likely to have fewer natural enemies in their area of introduction than in their native range. This can increase the chances of the introduced species becoming invasive but it does mean that, other things being equal, the new crop is less likely to act as a source of pests for other crops.

Invasions resulting from degradation of wild areas and land clearance for plantations and production systems

As previously outlined, "disturbance" can facilitate the spread of invasive species. Logically speaking, it could be assumed that converting land for biofuel crop production – as with all agricultural practices - could cause ecosystem disturbance and hence an enhanced risk of species invasions. However, it is possible to integrate sustainable land management practices into biofuel feedstock production systems in such a way that disturbance is minimised. This idea will be revisited when considering management tools that could be utilised to minimise the invasive species impacts of a growing biofuel industry.

6. Invasive Species Management Tools and their Application to Biofuel Production Systems

A range of tools have been developed in recent years to mitigate the negative impacts of invasive species. These tools can be used, together with those developed in other sectors, to maximise the opportunities resulting from an expanding biofuel industry while minimising the risks. IUCN has compiled principles, frameworks and tools already in use in the conservation community, such as impact assessment tools, forestry tools and certification, standards, labelling, and invasive species management tools, which can be applied to biofuel production systems (Keam and McCormick 2008). This section examines available invasive species management tools in more detail as a foundation upon which to build guidelines to prevent, ameliorate or manage negative invasive species impacts of biofuel production systems.

The first priority of invasive species management is prevention.

The old adage that "*an ounce of prevention is worth a pound of cure*" certainly holds true when it comes to invasive species. Emphasis on prevention is the underlying principle of phytosanitary policy as outlined in the IPPC (Lopian 2003) and the Convention on Biological Diversity (CBD) as enshrined in its Guiding Principles on Invasive Alien Species (CBD 2002, Decision VI/23). Guiding Principle 2 states that the first priority of invasive species management is prevention. If the species has already been introduced but is not abundant then early detection and rapid response (ideally eradication) are recommended. If this fails, the third stage is containment and long-term control. Eradication and control, while sometimes possible, are far from certain and may be very expensive (Simberloff 2008). Although not emphasised in the CBD Guiding Principles, ecosystem restoration, using a variety of landscape management techniques, might be necessary should containment and control be insufficient to rehabilitate an invaded ecosystem to its desired state.

Prevention

Effective prevention is an integrated process encompassing species selection, risk assessment, a regulatory framework and quarantine measures.

Selection of native species as biofuel crops

Subjecting a shortlist of plants selected as candidate biofuel crops to a weed risk assessment can screen out potentially invasive species. Another possibility is to choose native species as biofuel crops. As previously outlined, native species can become invasive, usually as a result of ecosystem changes. However, the likelihood of this is much lower than it is for introduced species. On the other hand, if native species are bred especially to improve certain traits, there is greater risk that wild races could be affected. Increased emphasis on the selection of native species as biofuel crops might result in higher research costs as relatively high numbers of species would need to be screened.

GENETIC MANIPULATION TO REDUCE INVASIVENESS

Breeding for sterility can considerably reduce the risk of a species becoming invasive (Lewandowski *et al.* 2000). For example, so far there are no records of escape of the sterile biofuel feedstock miscanthus (*Miscanthus* × *giganteus*) (native to Asia) after nearly 30 years of field research across Europe despite the fact that one of the parent species (*Miscanthus sinensis*) is invasive in the United States and elsewhere (Lewandowski *et al.* 2000). However, sterility does not guarantee non-invasiveness. Examples of species that are invasive in spite of sterility are the proposed biofuel crop giant reed (*Arundo donax*), parrots feather (*Myriophyllum aquaticum*), soursob (*Oxalis pes-caprae*) and Japanese knotweed (*Polygonum cuspidatum*) (Barney and DiTomaso 2008) and perpetual sterility cannot be guaranteed (Gray *et al.* 1991). There are also socio-economic implications of sterile feedstock to consider, depending on the reproductive cycle of a feedstock species, and whether a farmer is required to purchase seeds/cuttings rather than collect and re-use their own.

PLANT RISK ASSESSMENT

Screening systems are needed to help us determine whether the risk of introducing a species, to a country or within a country, is acceptable. Several plant risk assessment tools have been produced for different countries and ecosystems within countries for this purpose. Available examples include woody invaders of North America (Reichard and Hamilton 1997), woody invaders of the South African Fynbos (Tucker and Richardson 1995) and weeds in Australia (Pheloung *et al.* 1999).

The Australian system quoted is a simple spreadsheet requiring answers to questions about the traits of a species, dispersal, habitat suitability, invasion history elsewhere and impacts. There are 49 questions, not all of which need to be answered. The answers are given numerical scores which are added together and the overall score compared with numerical decision criteria which will result in a recommendation to approve a species for importation, reject the species or a recommendation for further evaluation.

The Australian system has been tested in Australia against expert scores for both weeds and non weeds from the agricultural, environmental and other sectors. All taxa classified as serious weeds, and most minor weeds, were rejected or required further evaluation, while only 7% of non-weeds were rejected. This system, with some minor modifications, has since been tested in New Zealand, Hawaii, Hawaii and Pacific Island, Czech Republic, Bonin Islands and Florida. Analysis of those results showed that the system rejected an average of 90% of major invaders; accepted major invaders less than 5% of the time and rejected non-invaders up to 23% of the time. Based on these results, this system has been recommended for adoption as an initial screen for proposed new plant introductions (Gordon *et al.* 2008).

Buddenhagen *et al.* (in press) used the modified Australian system to compare invasion risks of a comprehensive list of 40 biofuel species proposed for Hawaii versus a random sample of 40 introduced non-biofuel species. Two-thirds of the biofuel species had a high risk of becoming invasive versus one-quarter of non-biofuel species.

In principle, risk assessment schemes can be used to assess the risks of genetically modified species becoming invasive (Barney and DiTomaso 2008). However, it will take some time before all the traits of the newly modified species become clear so in practice the emergence of novel species is likely to complicate risk assessment (Simberloff 2008).

The use of risk assessments to justify phytosanitary measures (such as exclusion, control and containment) is consistent with the IPPC, to which 170 governments adhere (as of 10 September 2008). However, only a few countries, notably New Zealand, exclude new introductions unless subject to a risk assessment. In addition, a reject score for most countries does not necessarily mean that the species in question will be excluded and the final decision on importation rests with the importing authority (Quinlan *et al.* 2003).

7. Risk Management Measures

Risk assessment by its very nature cannot be foolproof so there is a chance that even species deemed to be low risk may become invasive. One means of risk minimisation is the granting of an importation permit with conditions that help to minimise the risk of the species in question becoming invasive (Shine *et al.* 2000). Appropriate conditions may include the preparation of a monitoring and contingency plan (including an eradication, containment or control plan) and the implementation of a system of bond payments to help finance mitigation operations in case of escape. A similar system of post-entry evaluation could be undertaken for those species recommended for further evaluation as used for genetically modified crops in some countries (Cousins 2008).

The principal means of managing risks associated with seed contaminants is treatment and inspection of the batch prior to the issue of a phytosanitary certificate. This certifies that the consignment is considered to conform to the current phytosanitary requirements of the importing contracting party and that the consignment has not been subject to the risk of infection or pest infestation. ISPM 12 (2001) gives detailed guidelines to assist National Plant Protection Organisations (NPPOs) with the preparation and issue of phytosanitary certificates.

Early detection, rapid response and eradication

There have been many successful invasive species eradications, notably those of diseases and disease vectors from islands and mainland areas and mammals from islands (Simberloff 2002). Examples include the eradication of smallpox from the face of the earth (Fenner *et al.* 1998), the eradication of the African mosquito *Anopheles gambiae*, a vector of malaria, from 31,000 km^2 of north-eastern Brazil (Davis and Garcia 1989) and the eradication of the Norway rat (*Rattus norvegicus*) from the 11,268 ha Campbell Island (New Zealand) (Towns and Broome 2003).

Plant eradication, however, is notoriously difficult unless the invasion is detected in its very early stages (Mack and Lonsdale 2002). If escape is not detected early enough, and if the species has spread to multiple locations or to inaccessible places, then eradication is highly unlikely. To maximise the possibility of eradication success, therefore, an effective monitoring system is required for the early detection of individual plants that escape from cultivation. This should be linked to a rapid response system that provides the administrative, financial and technical support for a successful eradication.

For an eradication to be successful, all individuals, including those that have been planted, must be removed to prevent further reinfestation. Efforts to target all plants can meet with opposition where the species in question is useful and not yet causing negative impacts (Soria *et al.* 2002). In such cases, education and awareness raising programmes need to be incorporated into the eradication campaign. If stakeholders

Plant eradication is notoriously difficult unless the invasion is detected in its very early stages.

cannot agree to an eradication programme then management may have to aim for containment and control.

Containment and control

Control measures are used to maintain the target species to a density at which it does not jeopardise economic, social, economic and environmental objectives such as land improvement, water conservation, access to land and the conservation and sustainable use of biodiversity. The aim of containment is to restrict the invader to a defined area, ideally the plantation in the case of a biofuel crop. Manual, mechanical, chemical, cultural, biological or integrated methods are possible options for containment and control. Initial control costs can be very high. In South Africa for example, initial weeding costs in the Working for Water programme can be as high as 7000 Rand per ha for densely infested areas (R6.50–7.50: US$1), but the maintenance weeding costs decrease with each treatment. As long as there are seed banks of invasive plants or nearby seed sources, treatment must be maintained but this treatment is not intensive, costing less than R50 per ha per treatment, which could be every 1–3 years, if carried out regularly (Turpie *et al.* 2008). Although expensive, the programme has been shown to be economic with more water delivered at a lower cost when control operations were undertaken than when they were not (van Wilgen *et al.* 1998).

Classical biological control, where a specific natural enemy from the species' native range is introduced to control an invading species, offers the possibility of sustained control with minimal recurrent input. If a biological control programme conforms to established guidelines (e.g. ISPM 3 - code of conduct for the import and release of exotic biological control agents) the likelihood that the control agent will become a pest is low. However, a biological control programme can be expensive to establish if existing agents are not already available (Harris 1979) and success is not guaranteed (Julien 1992). An additional complication might be the need to reconcile conflicts of interest between those who are negatively impacted by the species invasion and those who derive benefit from the species. In such cases it may be possible to introduce a biological control agent that reduces the invasiveness of the species while having little impact on the economically important part of the plant. The extensive use of host-specific seed-feeding biological control agents to curtail the spread of woody species in South Africa is an example of such an approach (Zimmerman *et al.* 2004).

Restoration

Species removal alone may not be sufficient to restore an ecosystem to its desired state

Invasive species eradication, containment and control often results in very positive ecosystem outcomes (Simberloff 2002, Rejmánek and Pitcairn 2002). However, species removal alone may not be sufficient to restore an ecosystem to its desired state (Zavaleta *et al.* 2001). In such cases an integrated approach to ecosystem restoration, encompassing invasive species control or eradication and additional actions such as revegetation, nutrient enrichment, species reintroduction and modification of grazing regimes, will be required (Berger 1999). The precise nature of the restoration programme will depend upon stakeholder priorities, the costs and benefits of particular restoration techniques, and the relative economic, social and environmental values of the land in its current and desired future state. Like control costs, restoration costs can be high but must be judged in terms of the balance between costs and their benefits over a number of years.

If carefully planned, at a scale consistent with available resources, biofuel production systems could become part of the ecosystem restoration arsenal rather than a potential source of ecosystem degradation (Field *et al.* 2007). Native or non-invasive introduced biofuel feedstock species have the potential to contribute to the restoration of degraded lands; for example, as "nurse plants", habitat to indigenous fauna, in the sequestration of toxic chemicals, and as aids to aquifer recharge and soil restoration (Ewel and Putz 2004). Systems managed for multipurpose goals such as biofuel feedstock production and landscape restoration will not be the biodiversity equivalents of old-growth forests (Hobbs *et al.* 2006) but they do have the potential to conserve many of the components of the original biodiversity (Chazdon 2008).

8. Discussion

Our understanding of the causes and consequences of biological invasions and our ability to assess invasive species risks has increased considerably in recent years (Barney and Whitlow 2008). In addition, a suite of tools and approaches to prevent and manage biological invasions has now been produced (Cousins 2008, Reaser *et al.* 2008, Weber *et al.* 2009). Most of these tools and approaches have been developed as a response to invasive species problems that have arisen as a result of well-intentioned efforts to enhance human wellbeing.

This paper has outlined the particular invasive species risks posed by an expanding biofuel industry, through both the type of feedstock and the production methods chosen. It is essential that invasive species expertise is brought on board when planning biofuel feedstock policies and investment so that unforeseen consequences are mitigated. If not, it seems likely that invasive species experts will eventually be involved but in a reactive and not proactive capacity.

Key Definitions

BIOENERGY & BIOFUELS
• BIOENERGY: Energy produced from biomass whether for heat, electricity or transport. • BIOFUELS: Liquid or gaseous fuels produced from biomass that can be used to replace petrol, diesel and other transport fuels. • BIOETHANOL: Petrol replacement produced from sugar or starch crops such as sugarcane, sugarbeet, maize and wheat. These crops are grown almost entirely as monocultures on fertile soil. • BIODIESEL: Diesel replacement composed of methyl (or ethyl) esters of long chain fatty acids derived from plant oils such as rapeseed, palm oil and soy. • BIOGAS: Gas produced from anaerobic digestion or fermentation of biomass and composed mainly of methane and carbon dioxide. Biogas can be burnt to produce heat and/or electricity or upgraded for use in vehicles that run on compressed natural gas (CNG) or liquid petroleum gas (LPG). • FIRST GENERATION (1G): Biofuels produced from existing food and feed crops using simple and well established processing technologies (nearly all biofuels are currently first-generation). • SECOND GENERATION (2G): Biofuels produced from a wider range of cellulosic biomass including agricultural wastes and plant species grown specifically for their biomass such as switchgrass and willow and converted using more advanced thermo-chemical or bio-chemical processes. Crops could be grown on more marginal land, using lower amounts of inputs than first generation biofuels and the feedstock could be more diverse. • THIRD GENERATION (3G): Potential future biofuels produced from “energy-designed” feedstocks with much higher production and conversion efficiencies than current biofuels. e.g. biofuels from algae cultures.
INVASIVE SPECIES
• NATIVE SPECIES: Species or genotype that is indigenous to a country or area. • NON-NATIVE OR ALIEN SPECIES: Species, subspecies or lower taxon, introduced outside its natural past or present distribution; includes any part, gametes, seeds, eggs, or propagules of such species that might survive and subsequently reproduce (CBD Decision VI/23). • INVASIVE ALIEN SPECIES: A species (of animal or plant or microorganism) which invades a new area causing negative impacts on biodiversity, ecosystem services (watershed protection, nutrient cycling, etc.), agriculture, human development and human health. • PEST: Any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products … In applying these initiation points to the specific case of plants as pests, it is important to note that the plants concerned should satisfy this definition. Pests directly affecting plants satisfy this definition. In addition, many organisms indirectly affecting plants also satisfy this definition (such as weeds/invasive plants) ([IPPC, 2004). • INTRODUCTION: The movement by human agency, indirect or direct, of an alien species outside of its natural range (past or present). This movement can be either within a country or between countries or areas beyond national jurisdiction (CBD Decision VI/23). • INVASIVE SPECIES PATHWAY: The means or route by which an invasive species is moved intentionally or unintentionally from its place of origin (or recent habitat) to an area where it has not been before (e.g. the horticulture trade, food aid and tourism). • INVASIVE SPECIES VECTOR: The agent or mechanism that has assisted an invasive species to move along a pathway (e.g. vehicles, people travelling, containers, luggage, wind, water currents).

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