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Mitigation of indirect environmental effects of GM crops

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Currently, the UK has no procedure for the approval of novel agricultural practices that is based on environmental risk management principles. Here, we make a first application of the 'bow-tie' risk management approach in agriculture, for assessment of land use changes, in a case study of the introduction of genetically modified herbicide tolerant (GMHT) sugar beet. There are agronomic and economic benefits, but indirect environmental harm from increased weed control is a hazard. The Farm Scale Evaluation (FSE) trials demonstrated reduced broad-leaved weed biomass and seed production at the field scale. The simplest mitigation measure is to leave a proportion of rows unsprayed in each GMHT crop field. Our calculations, based on FSE data, show that a maximum of 2% of field area left unsprayed is required to mitigate weed seed production and 4% to mitigate weed biomass production. Tilled margin effects could simply be mitigated by increasing the margin width from 0.5 to 1.5 m. Such changes are cheap and simple to implement in farming practices. This case study demonstrates the usefulness of the bow-tie risk management approach and the transparency with which hazards can be addressed. If adopted generally, it would help to enable agriculture to adopt new practices with due environmental precaution.

Keywords: genetically modified crops; environmental risk assessment; sugar beet; mitigation; biodiversity

1. INTRODUCTION

The UK has a well-developed and tight procedure for assessing the risks of the introduction of genetically modified (GM) crops. However, there is no such regulatory scrutiny of the introduction of novel non-GM agricultural practices; some of these (such as the switch from spring to autumn cereal cropping) have had profound effects on farmland biodiversity (ACRE 2006). Furthermore, there is still no formal risk management procedure for either the introduction of GM crops or novel non-GM agricultural practices, although the ACRE Committee has recognized the importance of the balance between risks and potential benefits (ACRE 2005).

Risk assessment lies at the heart of risk management and one of the most powerful and increasingly well-accepted approaches for considering risks is the bow-tie method (Crerand 2005). Importantly, this method highlights the links between risk controls and the underlying management system and clearly illustrates the relationship between hazards, causes, consequences and controls. This methodology has been widely adopted in the chemical and engineering sectors (see www.chemical processing.com/articles/2005/612.html), but has not penetrated the land use environmental sector. The increasing concern about the environmental risks of agriculture and the furore surrounding GM crops highlight the need for effective and trusted risk management to be adopted and the bow-tie method could offer an important solution to the stalemate perceived in the European GM agricultural sector.

The bow-tie methodology comprises a synergistic adaptation of three powerful conventional system safety techniques: fault tree analysis, causal factor charting and event tree analysis (Gifford *et al*. 2003). The completed bow-tie diagram (figure 1) illustrates the hazard, its causes and consequences, and which control measures can be adopted to minimize the risk. The diagram can be used to clearly demonstrate to stakeholders how hazards may be controlled or prevented by a series of management or mitigation activities. The bow-tie diagram includes a pre- and a post-event side; it uses 'barriers' to illustrate mitigation activities and depicts the consequences of the mitigated event. All stakeholders interested in the risk assessment and management can see how the process is working and how risks are being assessed and managed, which can be critical for enhancing confidence in the regulatory process (Johnson *et al*. 2007). The bow-tie technique was developed by the petrochemical business Shell to address and integrate the requirements of classical probabilistic risk assessment together with ideas about how accidents happen (Wagenaar *et al*. 1994; Vd Graaf *et al*. 1996). The basis is that one can envisage a series of barriers which are placed between the hazards and the outcomes to be avoided. The barriers are the defences and the holes are the weaknesses in those defences (Reason 1990, 1997). All defences/barriers have some weaknesses/holes with earlier defences attempting to stop hazards being released, and later defences showing how hazards even when occurring, can still be controlled or contained. An important aspect of these models for GM risk management relates to the fact that many of the causes of an accident, for example, gene flow into a wild relative resulting in decline of an important non-target organism,
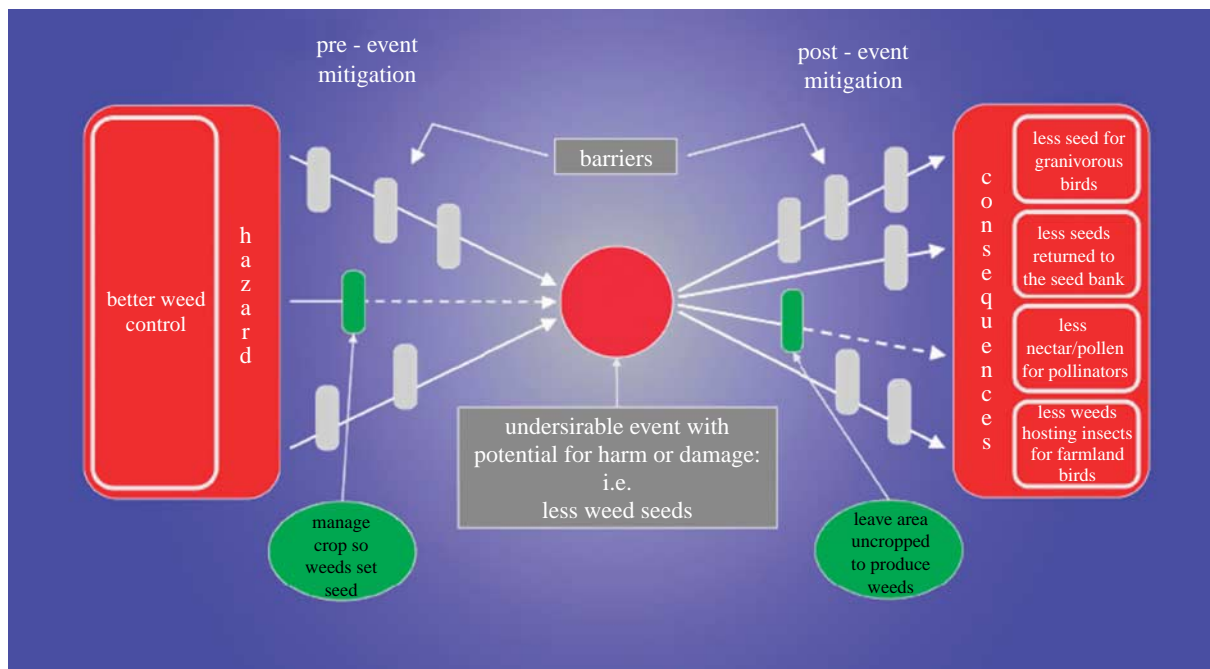
Figure 1. Bow-tie risk mitigation using GMHT sugar beet as an example. In the pre-event phase, there may be single or multiple barriers (the grey boxes) that could prevent the undesirable outcome. Similarly, post-event mitigation may be feasible with single or multiple barriers to prevent the consequences. For GMHT beet, a single pre-event mitigation (green box; manage crop so weeds set seed) is discussed and a single post-event mitigation (leave uncropped/unsprayed areas) is demonstrated.

can be identified in advance and thus be part of the risk assessment and management. The bow-tie diagram also illustrates how well defended an operation/practice is and how many and what types of barrier are preventing the undesirable consequences from occurring.

The approach is widely used in oil and gas industries and more recently has started to have impact in areas of medicine such as clinical pharmacy (Hudson & Guchelaar 2003). It is possible to use a range of software packages which use bow-tie analysis (e.g. Bow-Tie Pro, Thesis, Active Bow-tie) to manage risks and characterize the links between hazards, threats, barriers, consequences, recovery measures, tasks, people and procedures and these have become at the heart of corporate governance of risk for many industries. Another advantage of the use of a bow-tie model is that it also provides a unified structure for incident analysis and audits. There is considerable fear about possible 'incidents' involving GM crops (Poortinga 2005); the use of the bow-tie approach can not only minimize the likelihood of the detrimental effect, but also outline how to mitigate its impact and if necessary audit any incidents which do breach the system.

Here, we examine the application of the bow-tie method to the possible introduction of GM herbicide tolerant (GMHT) sugar beet into the UK. This is an important case study since GMHT beet would bring major agronomic and economic benefits to farmers (May 2003). These are increasing in potential importance as the EU sugar regime reform is reducing the profitability of sugar beet production seriously. As a spring crop, sugar beet delivers important diversity to the predominantly winter cropping arable landscape of England (Jaggard & Dewar 2005). Thus, there are both economic and environmental benefits in managing and mitigating the environmental risks associated with growing GMHT beet. Such benefits would be critical to the cost/benefit analysis of introducing such a crop, but cannot be included in a risk

assessment. However, managing the environmental risk via bow-tie methods can be important in the overall risk management and risk communication process.

Arable farmland in Europe has a multifunctional role. There is particular concern in the UK over the decline in populations of some farmland bird species (Chamberlain *et al.* 2000; Donald *et al.* 2001). Against this background, the proposed introduction of GMHT sugar beet in England raised concerns that improved weed control (Moll 1997) might result in further impoverishment of farmland wildlife (English Nature 1998, 2000), at several trophic levels, especially farmland birds. Furthermore, since spring-sown crops often replenish seed bank losses in cereal phases of common rotations, such undesirable impacts might persist over several growing seasons.

In response to these concerns, the farm scale evaluations (FSE) of genetically modified crops compared the effects on farmland wildlife indicator species of the GMHT crop, under a single management system. For sugar beet, this was an intensive two-spray system designed to maximize weed control in a cost-effective manner. No effects were found due to the crop being genetically modified *per se* (Firbank *et al.* 2003; Hawes *et al.* 2003). However, differences were found in weed flora (Heard *et al.* 2003a,b) between the conventional crop and the GMHT crop under this weed management regime. It was also demonstrated that changes in invertebrate fauna depend on the changes in the weed communities (Hawes *et al.* 2003). The key differences between GMHT and conventionally managed sugar beet were: (i) reduced final weed biomass (17% of conventional) and total weed seed rain (31% of conventional) in the GMHT crop and (ii) reductions (66 and 61%, respectively of conventional) in flowering and seeding of broad-leaved weeds in the tilled margin of the GMHT crop. Using bow-tie methods, we illustrate how the risk of growing GMHT beet could be managed via a series of pre- and post-event barriers, which can be considered as barriers to preventing the threat
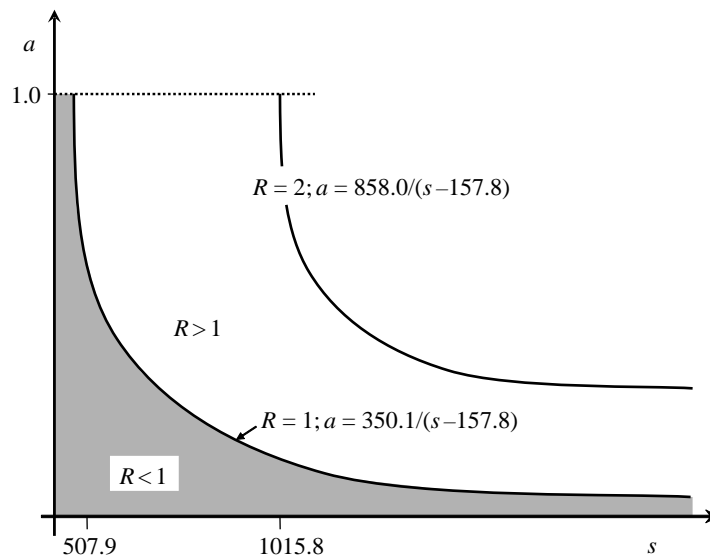
Figure 2. The relationship between a, the proportion of rows of GMHT sugar beet required to be untreated with herbicide and s, the number of dicotyledonous seeds per square metre per year entering the seed bank from a cropped but untreated area, to achieve various values of R, the ratio of the resulting overall dicotyledonous seed rain for GMHT management as a ratio of that for conventional management. For any given value of R, the relationship between a and s is a rectangular hyperbola and for any given estimate of s, the larger the required value of R, the larger a must be to mitigate. To achieve equivalent seed rain as conventional management ($R=1$) would require $a>350.1/(s-157.8)$, while to achieve double this amount would require a value of a of about 2.5 times greater.

or recovery measures, respectively (figure 1). Central to the bow-tie is the 'top event', which is the first consequence caused by the release of the hazard. In the case of GMHT beet, this would be the reduction in weeds within the sprayed field.

For GMHT beet, a range of approaches has been developed that provide either early season environmental benefits (for insectivorous birds) or late season environmental benefits (for granivorous birds and weed seed bank recharge), and crucially do so without significant yield or profitability reductions (Dewar *et al.* 2003; May *et al.* 2005). This is pre-event mitigation that stops the event/hazard from occurring, thus stopping the top event from happening in the first place (figure 1). However, it might well be the case that growers would wish to persist with the simple two-spray management approach (as tested in the FSE trials), thus causing the hazard (reduction of weeds within the sprayed GMHT beet) to be released. In the bow-tie system, this would require post-event mitigation (one in which the hazard is still realized but the consequences are managed). The simplest mitigation is to leave a proportion of rows of beet fields unsprayed to promote the production of flowering and seeding arable weeds. Adoption of spatial separation at the field level has already been proposed (e.g. Meek *et al.* 2002; Green *et al.* 2005), although not in relation to mitigation of increased weed control in GMHT crops. We have modelled the possibility of providing such a post-event mitigation of allowing additional flowering weeds and weed seeds to be produced within the field and available for granivorous birds in the autumn. Thus, the consequences of a reduction in the biodiversity associated with weeds are addressed/overcome by specific recovery measures incorporated into management practice. In this paper, we have analysed data from the FSE to predict the proportion of each field under GMHT management that would need to be unsprayed and achieve the equivalent amount of seed rain to that obtained under conventional management in

the FSE. We then examine whether this approach would be realistic in commercial farming. We also address the problem of the reduced weed seed bank in the remainder of the field and show how this issue may be addressed by an occasional fallow season.

2. MODEL

Let the total dicotyledonous seed rain in one season in an area cropped with sugar beet but untreated with herbicide be denoted as s (m^{-2}). Suppose that a proportion, a, of the rows of a field is untreated and that the remaining proportion, $1-a$, receives GMHT management as practised in the FSE. Let R represent the dicotyledonous seed rain for this mitigated GMHT management as a ratio of that for conventional management. With no mitigation, when $a=0$, the expected value of R would be 0.31, as found in the FSE by Heard *et al.* (2003*a*) and the seed rain would be $157.8 \, m^{-2}$ (compared with the equivalent expected value for conventional management of $507.9 \, m^2$). In the mitigated system, the expected seed rain m^{-2} is $(157.8(1-a)+as)$ and $R=(a(s-157.8)+157.8)/507.9$. For any given value of R, the relationship between a and s is described by a rectangular hyperbola (figure 2) so for any given estimate of s, the larger the required value of R, the larger a must be to mitigate. To achieve at least as much seed rain as conventional management ($R=1$) would require $a_1>350.1/(s-157.8)$ (unshaded region, figure 2) while to achieve double this amount ($R=2$) would require $a_2>858.0/(s-157.8)$. A more conservative estimate for a arises from the use of the lower 95% confidence limit for R of 0.19 given by Heard *et al.* (2003*a*), which would assume values per square metre for seed rain under conventional and GMHT of 648.8 and 123.5, respectively, instead of the values, 507.9 and 157.8, respectively, used above. Then, to achieve a value of exactly $R=1$ in the mitigated system would require the considerably larger value of $a_{1c}=525.3/(s-123.5)$.

To determine the values of a for the required levels of weed seed rain in the mitigated system requires estimation of the crucial parameter s. There were no unsprayed areas in the FSE trials and hence s could not be measured directly. We estimate s both indirectly, from analysis of FSE data, and directly, from four trials carried out in 2001 and 2002 which contained an unsprayed treatment (May et al. 2005) and in which over 97.5% of weeds sampled were dicotyledonous. Finally, we check that these approaches give consistent results.

3. ANALYSIS

The direct estimate of s comes from the total dicotyledonous seed rain per square metre in sugar beet crops at the four sites described above which were 4.1×10^4, 5.41×10^4, 6.8×10^3 and 3.0×10^4 at sites 1–4, respectively. The geometric mean of these values was 2.60×10^4, with 95% CI of $(5.17 \times 10^3, 8.59 \times 10^4)$.

The indirect estimate of s was computed from the 3 years of the FSE data of Heard et al. (2003a). Briefly, the approach was to model the dependence of seed rain, s, by multiple regressions on the rate and timing of herbicide applications, using as covariate the 'first-seedling' count, c, (Heard et al. 2003a) made between crop sowing and the application of the first conventional post-emergence herbicide. Having established the regression model, extrapolation was then used to estimate the seed rain in the absence of herbicide treatment. Full details are given in the electronic supplementary material. The estimated value of s was 3.55×10^4 seeds m^{-2}, with approximate 95% CI of $(5.35 \times 10^3, 2.35 \times 10^5)$.

Therefore, results from this predictive analysis from the large FSE dataset, when interpreted to give a conservative estimate, agreed closely with the smaller field trials reported above. Using the value of $s = 2.60 \times 10^4$ seeds m^{-2} from the field trials, the value of a required to mitigate GMHT management to achieve a value of $R = 1$, in which seed rain production is equivalent to that under conventional crop management, was $a_1 = 0.0136$. To achieve $R = 2$ (double the seed rain of a conventional system) would require $a_2 = 0.0332$. To achieve $R = 1$, if the lower confidence limit of the effect of GMHT relative to conventional from Heard et al. (2003a) is assumed, would require $a_{1c} = 0.0203$. Using the value of $s = 3.55 \times 10^4$ seeds m^{-2}, the equivalent values are: $a_1 = 0.00990$; $a_2 = 0.0242$; and $a_{1c} = 0.0149$.

In summary, for sugar beet crops, an expected mitigation of $R = 1$ would require not more than three rows to be unsprayed in every 200, or four rows per 200 for the pessimistic lower limit of Heard et al. (2003a); mitigation of $R = 2$ would require not more than seven rows in every 200. Similar calculations using data of May et al. (2005) for biomass of dicotyledons suggest that expected mitigation of $R = 1$ for biomass would require eight rows in every 200.

4. DISCUSSION

This mitigation method does not address the problem of the reduced weed seed bank in the bulk of the field because the spatial distribution of weed seeds in mitigated fields will be highly aggregated around the unsprayed rows. Of course, if different rows were selected for mitigation, each time the crop was grown this problem would be ameliorated. Even without such an approach, an

occasional fallowing of the field would achieve seed bank recharge. Since the predicted rate of seed bank decline would be approximately 10% per year under a GMHT system (Heard et al. 2003b) and the population growth rate for unsprayed fields exceeds 50-fold even in the presence of a crop, we calculate that fields would need to be fallowed for a growing season not more than once in every 35 years to achieve an equivalent seed bank recharge. An obvious alternative approach would be to reduce slightly the level of broad-leaved weed control in some or all of the cereal crops in the rotation. This would have little economic consequence (Lutman et al. 2003).

Since the tilled margin averaged approximately 0.5 m wide, the reduction in flowering broad-leaved weeds could be very simply mitigated by increasing the width of this margin proportionality, i.e. from 0.5 to 1–1.5 m.

The 'GM debate' has involved a wide range of stakeholders (GM Nation? 2003) and there is scepticism about the transparency and power of the current regulatory system (Poppy & Wilkinson 2005; Johnson et al. 2007). The bow-tie methodology is particularly powerful in illustrating all the interactions of a risk management to the users (in this case farmers) and regulators (in this case ACRE and HSE), whatever be the level of quantified knowledge available. Those observing the process can also see which threats/hazards are being considered and how they are either mitigated against before their occurrence or how recovery measures can be adopted to reduce/circumvent undesirable consequences. This is particularly relevant to GM studies, where there is often debate about the quantity and quality of relevant knowledge. Thus, the bow-tie method of risk management has the potential to bring new clarity and confidence to the GM debate. The precautionary principle is often seen by scientists as a barrier to development. Opponents of change often argued that it is not more precautionary to move forward carefully than to remain with current technology, often known to cause damage. The use of bow-tie methodology for agriculture may allow us to adopt new technologies with precaution and to allow competitive agronomic practice together with an environmental awareness and conscience.

5. CONCLUSIONS

We have shown how the bow-tie approach to risk management could be applied to the introduction of GMHT sugar beet. We have calculated the additional areas of field, and tilled margin, that would need to be left unsprayed in order to mitigate the effects of improved weed control in the GMHT crop. We have shown that these areas are small and easily managed. Leaving one row in every 50 unsprayed would achieve mitigation for weed seed production equivalent to current conventional practice. Any overall decline in weed seed bank in the rest of the field could, in simplistic terms, be mitigated by fallowing once every 35 years. This case study involving GMHT sugar beet demonstrates how a risk management-oriented approach to the assessment of the environmental impact of novel crops and agricultural practices could work. If this approach were adopted generally, it would enable agriculture to move forward with due environmental precaution, rather than be destined to fail to adopt

new technologies, and suffer consequent economic penalties, however avoidable the risks entailed might be.

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