Derivation of a Cropping System Transfer Function for Weed Management: Part 1 – Herbicide Weed Management

Graham Brodie*

Melbourne School of Land and Environment, Melbourne University, Dookie Campus, Nalinga Rd, Dookie 3647, Australia

Abstract: System behaviour is described by the transfer functions, which relate the system's output to one or more input variables. No-till cropping systems depend on herbicide inputs for weed management and crop yield optimisation. This paper derives the transfer function for crop yield potential as a function of herbicide input, in the presence of herbicide resistance in the weed population, using several mathematical components for crop and weed ecology from published literature. The resulting transfer function reveals the herbicide application rate for optimal crop yield potential and highlights the growing herbicide resistance problem in no-till cropping systems.

Keywords: System analysis, weeds, herbicide, herbicide resistance, crop ecology.

1. INTRODUCTION

System analysis techniques can be applied to most agricultural system in order to better understand their operation and optimise performance. System analysis usually includes the development of transfer functions [1]. Transfer functions are mathematical equations, involving various input variables or matrices, which relate the system's output to one or more of the system's inputs. In the case of an agricultural cropping system the key output from the system is potential crop yield. Some crop ecology studies have demonstrated that competition from weeds can reduce the potential yield of some crops by 35 % to 55 % [2,3].

Modern no-till cropping depends on herbicides for weed management; therefore herbicide applications are an important system input. Unfortunately, herbicide resistance in many weed species is becoming wide spread [4] and multiple herbicide resistances in several economically important weed species has also been widely reported [5]. In time, herbicide resistant weeds may ultimately result in significant yield reductions and grain contamination; therefore this paper derives a system transfer function relating herbicide input to potential crop yield in the presence of herbicide resistance, based on various ecological models published in literature.

2. DERIVATION OF CROP SYSTEM TRANSFER FUNCTION FOR HERBICIDE WEED MANAGEMENT

The effect of weed damage on crop yields can be described by the following [6]:

$$Y = Y_o\left[1 - D\left(R\right)\right] \tag{1}$$

In equation (1), D(R) is the damage function caused by a weed density of R, which represents the number of weeds that are recruited from the seed bank (plants m^{-1} of row). The Damage function can be described by the following equation [7]:

$$D\left(R\right) = \frac{I \cdot R}{100\left(e^{ct} + \frac{I \cdot R}{A_w}\right)} \tag{2}$$

Substituting equation (2) into equation (1) yields:

$$Y = Y_o\left[1 - \frac{I \cdot R}{100\left(e^{ct} + \frac{I \cdot R}{A_w}\right)}\right] \tag{3}$$

2.1. Herbicide Weed Management

Weed infestations will be made up of some resistant weeds (R_R) and some weeds that can be easily controlled by herbicides (R_S). After some kind of herbicide treatment, the density of susceptible weeds will be [6]:

$$R_s = R_{so}\left[1 - K\left(H\right)\right] \tag{4}$$

R_{So} is the initially susceptible weed density; K(H) is the kill function for the herbicide in this portion of the weed population for a given herbicide treatment of H. The resistant weed population will be [6]:

$$R_R = R_{Ro} \tag{5}$$

R_{Ro} is the initial resistant weed density. A typical kill function for a herbicide treatment is [8]:

*Address correspondence to this author at the Melbourne School of Land and Environment, Melbourne University, Dookie Campus, Nalinga Rd., Dookie 3647, Australia; Tel: +61 3 5833 9273; Fax: +61 3 5833 9201;
E-mail: grahamb@unimelb.edu.au

E-ISSN: 2409-9813/14

$$K\left(H\right)=1-e^{-\lambda H} \tag{6}$$

Substituting all these components into equation (3) yields:

$$Y=Y_o\left[1-\frac{I\left(R_{so}e^{-\lambda H}+R_{Ro}\right)}{100\left(e^{ct}+\frac{I\left(R_{so}e^{-\lambda H}+R_{Ro}\right)}{A_w}\right)}\right] \tag{7}$$

If p represents the portion of the population that is herbicide-resistant and R_o is the initial weed population density, then:

$$Y=Y_o\left[1-\frac{I\cdot R_o\left[\left(1-p\right)e^{-\lambda H}+p\right]}{100\left(e^{ct}+\frac{I\cdot R_o\left[\left(1-p\right)e^{-\lambda H}+p\right]}{A_w}\right)}\right] \tag{8}$$

The recruitment of seedlings from the seed bank can be described by the following equation [9]:

$$R_o=\frac{W}{1+e^{-\left(\frac{t-t_o}{d}\right)}} \tag{9}$$

Substituting this into equation (8) yields:

$$Y=Y_o\left[1-\frac{I\cdot W\left[\left(1-p\right)e^{-\lambda H}+p\right]}{100\left[1+e^{-\left(\frac{t-t_o}{d}\right)}\right]\left(e^{ct}+\frac{I\cdot W\left[\left(1-p\right)e^{-\lambda H}+p\right]}{A_w\left[1+e^{-\left(\frac{t-t_o}{d}\right)}\right]}\right)}\right] \tag{10}$$

This can be simplified to become:

$$Y=Y_o\left[1-\frac{I\cdot W\left[\left(1-p\right)e^{-\lambda H}+p\right]}{100\left(e^{ct}\left[1+e^{-\left(\frac{t-t_o}{d}\right)}\right]+\frac{I\cdot W\left[\left(1-p\right)e^{-\lambda H}+p\right]}{A_w}\right)}\right] \tag{11}$$

The portion of the population that is resistant to herbicide treatment will change from generation to generation depending on the selection pressure being applied by the herbicide treatments. Based on work by Gubbins and Gilligan [10], if there is a relatively constant selection pressure (s) towards herbicide resistance from generation to generation, then the following relationship will hold:

$$\frac{\partial p}{\partial g}=sp\left(1-p\right) \tag{12}$$

This partial differential equation can be solved by integration to give:

$$p=\frac{p_o e^{sg}}{1+p_o\left(e^{sg}-1\right)}\ and\ 1-p=\frac{1-p_o e^{sg}}{1+p_o\left(e^{sg}-1\right)} \tag{13}$$

Substituting these equations into equation (11) and simplifying yields:

$$Y=Y_o\left[1-\frac{I\cdot W\left[\left(1-p_o e^{sg}\right)e^{-\lambda H}+p_o e^{sg}\right]}{100\left(e^{ct}\left[1+e^{-\left(\frac{t-t_o}{d}\right)}\right]\left[1+p_o\left(e^{sg}-1\right)\right]+\frac{I\cdot W\left[\left(1-p_o e^{sg}\right)e^{-\lambda H}+p_o e^{sg}\right]}{A_w}\right)}\right] \tag{14}$$

There is also evidence that herbicides have a toxic effect on the crop as well. Using the study by Yin *et al*. [11] as a guide, and assuming that the toxicity of the herbicide on a crop can be expressed as a polynomial of the form $Loss=aH^2-BH$, equation (14) can be modified to become:

$$Y=Y_o\left[\begin{array}{l}1-\frac{I\cdot W\left[\left(1-p_o e^{sg}\right)e^{-\lambda H}+p_o e^{sg}\right]}{100\left(e^{ct}\left[1+e^{-\left(\frac{t-t_o}{d}\right)}\right]\left[1+p_o\left(e^{sg}-1\right)\right]+\frac{I\cdot W\left[\left(1-p_o e^{sg}\right)e^{-\lambda H}+p_o e^{sg}\right]}{A_w}\right)}\\+aH^2-bH\end{array}\right] \tag{15}$$

The seed bank will be dynamic depending on factors such as natural seed mortality, immigration of seeds into the area from other locations *via* various vectors, emigration of seeds out of the area to other locations *via* various vectors, the onset of dormancy that prevents germination in the current season, and the breaking of dormancy from previous seasons in the seed bank.

$$Y = Y_o \left[\begin{array}{l} 1 - \\ \dfrac{I \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right] \left[\left(1 - p_o e^{sg}\right) e^{-\lambda H} + p_o e^{sg} \right]}{100 \left(e^{ct} \left[1 + e^{-\left(\frac{t - t_o}{d}\right)} \right] \left[1 + p_o\left(e^{sg} - 1\right) \right] + \dfrac{I \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right] \left[\left(1 - p_o e^{sg}\right) e^{-\lambda H} + p_o e^{sg} \right]}{A_w} \right)} \\ + aH^2 - bH \end{array} \right] \tag{16}$$

2.2. Sensitivity Analysis

The development of transfer functions is not always for the purpose of providing accurate prediction but to provide insight into system behaviours as input parameters change. The sensitivity of the output to these changes can be assessed by differentiating the transfer function equations with respect to the input parameter of interest and assessing the magnitude of the resulting differential equation.

Differentiating equation (16) with respect to any of the key parameters allows sensitivity analyses to be performed. For example, differentiating equation (16) with respect to H determines the sensitivity of crop yield to herbicide weed treatments:

$$\frac{\partial Y}{\partial H} = Y_o \left[\begin{array}{l} \dfrac{\lambda I \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right] \left(1 - p_o e^{sg}\right) e^{-\lambda H}}{100 \left(e^{ct} \left[1 + e^{-\left(\frac{t - t_o}{d}\right)} \right] \left[1 + p_o\left(e^{sg} - 1\right) \right] + \dfrac{I \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right] \left[\left(1 - p_o e^{sg}\right) e^{-\lambda H} + p_o e^{sg} \right]}{A_w} \right)} \\ - \dfrac{\lambda I^2 \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right]^2 \left[\left(1 - p_o e^{sg}\right) e^{-\lambda H} + p_o e^{sg} \right] \left(1 - p_o\right)}{100 A_w \left(e^{ct} \left[1 + e^{-\left(\frac{t - t_o}{d}\right)} \right] \left[1 + p_o\left(e^{sg} - 1\right) \right] + \dfrac{I \cdot \left[W\left(1 - N - D_o\right) - E_m + I_m \right] \left[\left(1 - p_o e^{sg}\right) e^{-\lambda H} + p_o e^{sg} \right]}{A_w} \right)^2} \\ + 2aH - b \end{array} \right] \tag{17}$$

There is also replenishment of the seed bank due to seed set from survivors. Therefore equation (16) is only a static response transfer function. It is apparent that any crop-weed ecological modelling exercise must be performed in an iterative way, with the previous state of the weed seed bank influencing the current weed status [12]. The weed seed bank at the start of any cropping cycle, in simplified terms, can be understood as the sum of the dormant seed bank and the seed set from survivors of the previous season's weed management strategies; therefore an iterative approach to weed studies must be adopted [12,13]. This can be approximated by the following equuation:

$$W_i = \frac{\left[W_{i-1}\left(1 - N_{i-1} + D_b\right) - E_m + I_m \right] \left[\left(1 - p_o e^{sg_{i-1}}\right) e^{-\lambda H} + p_o e^{sg_{i-1}} \right] \cdot S_s}{1 + e^{-\left(\frac{t - t_o}{d}\right)}} + D_o W_{i-1} \tag{18}$$

Herbicide resistance in many weed species is becoming more prevalent [4,14]. Thornby and Walker [15] simulated continuous summer fallows using glyphosate. Their modelling showed that barnyard grass (*Echinochloa colona*) could become resistant to glyphosate in about 15 years. Validation of their model against paddock history data for glyphosate-resistant population of barnyard grass showed that their model correctly predicted resistance development to within a few years of the real situation.

Selection pressure for genetic traits depends on the initial efficacy of the herbicide to remove susceptible individuals from the population, leaving only the resistant individuals to reproduce. This is reinforced by the adoption of a single herbicide over a long period of time to sustain the selection pressure on the population.

3. METHOD

Equations (16), (17) and (18) were coded into a simple cropping system model using the MatLab software platform. Using data published by Bosnić and Swanton [8] and Yin *et al*. [11] for Rimsulfuron herbicide and assuming: an initially small resistant population ($p_o = 1 \times 10^{-8}$); an average seed set of 700 seeds per weed plant; a seed mortality rate of 10 % each year; and a slightly positive selection coefficient of ($s = 1 \times 10^{-4}$) for herbicide resistance [16], the system transfer function was used to analyse the effect of a single herbicide application on crop yield potential. The transfer function was also used to forecast the viable weed seed bank and long term crop yield potential, assuming that only a single herbicide type was used during this time.

4. RESULTS AND DISCUSSION

Figure **1** shows the expected crop response as a function of the herbicide's application rate. There is an optimal application rate of about 0.009 kg ha^{-1}, based

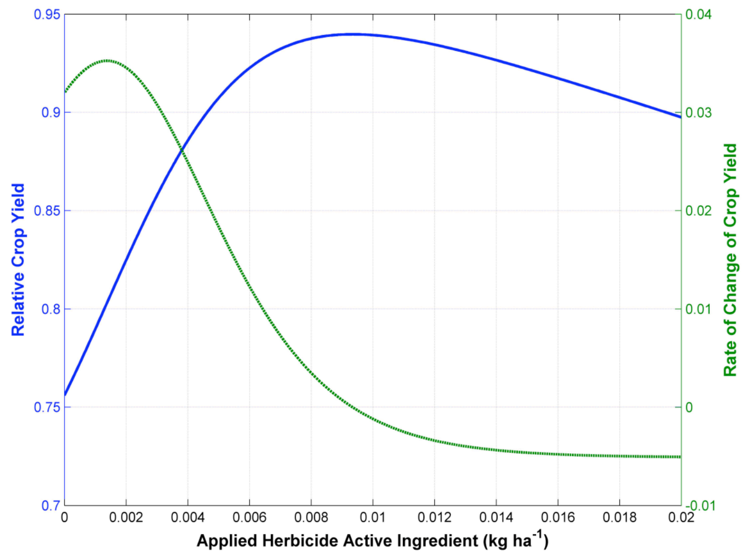

Figure 1: Normalised crop yield (blue line) and rate of change (green line) of crop yield response as a function of applied herbicide energy, based equations (16) and (17).

on these parameters, while the maximum rate of crop yield response (where $\frac{\partial Y}{\partial H} = 0$) occurs at about 0.001 kg ha^{-1}. The transfer function also predicts that significant herbicide resistance will occur within 15 generations (Figure **2**), as was also predicted by Thornby and Walker [15]. Herbicide rotations can forestall the development of a resistant population; however several weed species have developed multiple resistance to several herbicide groups [5].

A growing herbicide resistance problem is already evident in most Australian cropping systems [17,18]. There is evidence that glyphosate resistance has already developed in some weed populations [17] and multiple herbicide resistances has been widely reported in several weed species [5,19-21]; therefore significant crop yield (Figure **2**) losses can be expected. Alternative weed management strategies that are compatible with no-till cropping systems need to be developed.

5. CONCLUSION

This paper has developed a cropping system transfer function relating herbicide application to potential crop yield. The transfer function also allows for herbicide resistance in the weed population and can be used to investigate the potential long term implications of herbicide weed control.

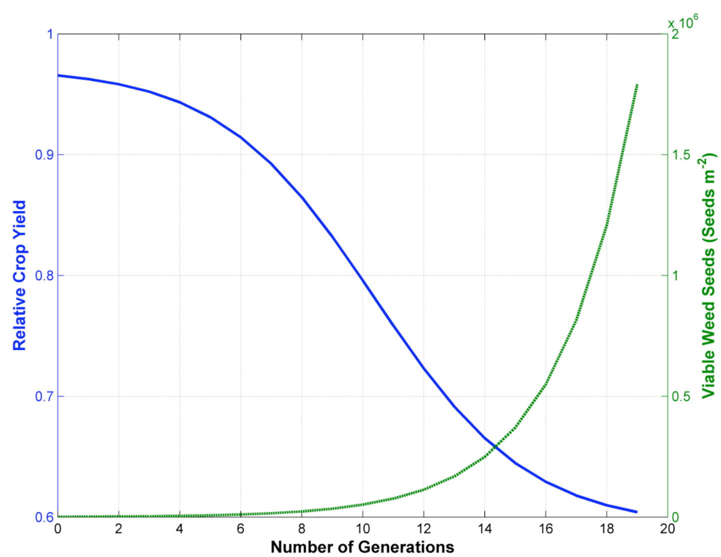

Figure 2: Generational impact of herbicide resistant weeds on potential crop yield (blue line) and viable seed bank (green line) under continuous herbicide weed management, based on equations (16) and (18).

ACKNOWLEDGEMENTS

This work has been made possible with the generous support of the Australian Rural Industries Research and Development Corporation (RIRDC) and the Australian Grains Research and Development Corporation (GRDC).

NOMENCLATURE

A_w Is the percentage yield loss as weed density approaches ∞ (= 38.0 [8])

c Is the speed of light (m s^{-1}) or the rate at which I approaches zero as t approaches ∞ (= 0.017 [8])

d Is the slope of the seed bank recruitment curve at t_o

D_o Fraction of the seed population developing dormancy (Note: this is expressed as a fraction of the initial seed bank population W_o)

D_b Fraction of the seed population from previous seasons breaking dormancy (Note: this is expressed as a fraction of the initial seed bank population W_o)

E_m Seed emigration from the area of interest

g Is the generational number

H Is the herbicide dose

I Is the percentage yield loss as the weed density tends towards zero (= 0.38 [8])

Im Seed immigration into the area of interest

N Is the natural death rate for the whole population (Note: this is expressed as a fraction of the initial seed bank population W_o)

p_o Is the initial frequency of herbicide resistant plants

s Is the selection pressure for herbicide resistance

S_s Viable seed set per plant from surviving volunteers in the weed population

t Is the time difference between crop emergence and weed emergence

t_o Is the time for 50 % germination of the viable seed bank

W Is the viable seed bank

Y_o Is the theoretical yield with no weed infestations

λ Is the efficacy of the herbicide killing action

REFERENCES

[1] Åström KJ, Murray RM. Feedback Systems: An Introduction for Scientists and Engineers. Princeton University Press: Princeton. New Jersey 2012.

[2] Mondani F, Golzardi F, Ahmadvand G, Ghorbani R, Moradi R. Influence of Weed Competition on Potato Growth. Production and Radiation Use Efficiency. Notulae Scientia Biologicae 2011; 3(3): 42-52.

[3] Cathcart RJ, Swanton CJ. Nitrogen management will influence threshold values of green foxtail (Setaria viridis) in corn. Weed Science 2003; 51(6): 975-986. http://dx.doi.org/10.1614/P2002-145

[4] Heap IM. The occurrence of herbicide-resistant weeds worldwide. Pesticide Science 1997; 51(3): 235-243. http://dx.doi.org/10.1002/(SICI)1096-9063(199711)51:3<235::AID-PS649>3.0.CO;2-N

[5] Owen M, Walsh M, Llewellyn R, Powles S. Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (Lolium rigidum) populations. Australian Journal of Agricultural Research 2007; 58(7): 711-718. http://dx.doi.org/10.1071/AR06283

[6] Schmidt CP, Pannell DJ. Economic Issues in Management of Herbicide-Resistant Weeds. Research in Agricultural and Applied Economics 1996; 64(3): 301-308.

[7] Cousens R, Brain P, O'Donovan JT, O'Sullivan PA. The use of biologically realistic equations to describe the effects of weed density and relative time of emergence on crop yield. Weed science (USA) 1987;

[8] Bosnić AČ, Swanton CJ. Economic Decision Rules for Postemergence Herbicide Control of Barnyardgrass (Echinochloa crus-galli) in Corn (Zea mays). Weed Science 1997; 45(4): 557-563.

[9] Neve P, Norsworthy JK, Smith KL, Zelaya IA. Modelling evolution and management of glyphosate resistance in Amaranthus palmeri. Weed Research 2011; 51(2): 99-112. http://dx.doi.org/10.1111/j.1365-3180.2010.00838.x

[10] Gubbins S, Gilligan CA. Invasion Thresholds for Fungicide Resistance: Deterministic and Stochastic Analyses. Proceedings: Biological Sciences 1999; 266(1437): 2539-2549. http://dx.doi.org/10.1098/rspb.1999.0957

[11] Yin XL, Jiang L, Song NH, Yang H. Toxic Reactivity of Wheat (Triticum aestivum) Plants to Herbicide Isoproturon. Journal of Agricultural and Food Chemistry 2008; 56(12): 4825-4831. http://dx.doi.org/10.1021/jf800795v

[12] Pekrun C, Lane PW, Lutman PJW. Modelling seedbank dynamics of volunteer oilseed rape (Brassica napus). Agricultural Systems 2005; 84 (1): 1-20. http://dx.doi.org/10.1016/j.agsy.2004.06.007

[13] Bagavathiannan MV, Begg GS, Gulden RH, Van Acker RC. Modelling the Dynamics of Feral Alfalfa Populations and Its Management Implications. PLoS ONE 2012; 7(6): 1-10. http://dx.doi.org/10.1371/journal.pone.0039440

[14] Heap IM. International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/in.asp. (accessed 25th September 2008).

[15] Thornby DF, Walker SR. Simulating the evolution of glyphosate resistance in grains farming in northern Australia. Annals Of Botany 2009; 104(4): 747-756. http://dx.doi.org/10.1093/aob/mcp152

[16] Baucom RS, Mauricio R. Fitness costs and benefits of novel herbicide tolerance in a noxious weed. Proceedings of the National Academy of Sciences of the United States of America 2004; 101(36): 13386-13390. http://dx.doi.org/10.1073/pnas.0404306101

[17] Broster JC, Pratley JE. A decade of monitoring herbicide resistance in Lolium rigidum in Australia. Australian Journal of Experimental Agriculture 2006; 46 (9): 1151-1160. http://dx.doi.org/10.1071/EA04254

[18] Gill GS, Holmes JE. Efficacy of cultural control methods for combating herbicide-resistant Lolium rigidum. Pesticide Science 1997; 51(3): 352-358. http://dx.doi.org/10.1002/(SICI)1096-9063(199711)51:3<352::AID-PS648>3.0.CO;2-M

[19] Kuk YI, Burgos NR, Talbert RE. Cross- and multiple resistance of diclofop-resistant Lolium spp. Weed Science 2000; 48(4): 412-419. http://dx.doi.org/10.1614/0043-1745(2000)048[0412:CAMRODRL]2.0.CO;2

[20] Walsh MJ, Powles SB, Beard BR, Parkin BT, Porter SA. Multiple-Herbicide Resistance across Four Modes of Action in Wild Radish (Raphanus raphanistrum). Weed Science 2004; 52(1): 8-13. http://dx.doi.org/10.1614/WS-03-016R

[21] Yu Q, Cairns A, Powles S. Glyphosate paraquat and ACCase multiple herbicide resistance evolved in a Lolium rigidum biotype. Planta 2007; 225(2): 499-513. http://dx.doi.org/10.1007/s00425-006-0364-3

Received on 17-10-2014 Accepted on 01-11-2014 Published on 27-11-2014

DOI: http://dx.doi.org/10.15377/2409-9813.2014.01.01.2